PURDUE UNIVERSITY

Exploring Material-Process-Structure-Function Relationships in Additively Manufactured Energetic Materials

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25 YEARS OF ESTCP
2019 | Enhancing DoD's Mission Effectiveness

A Little Background…

- There has been significant research activity related to the development of additive manufacturing techniques capable of fabricating advanced geometries with an array of *classical materials*.

- There has been a much smaller portion of research related to additive manufacturing techniques compatible with *functional materials*.

- Our focus:
  - The development, and subsequent exploitation, of the processes and material systems necessary to realize additively manufactured energetic and reactive material systems (AMEM).

Additive Manufacturing of Energetic Materials: An Overview

- Electrospray Deposition
- Inkjet Printing
- Direct Write
- Fused Filament Fabrication
- Vibration Assisted Printing

(Potential) Benefits of AMEM:

- Geometric Flexibility
- Rapid Innovation in Design
- Potentially Lower Production Costs
- Waste Reduction
- Improved Process Safety
- Tunable, Functionally Graded Performance

Additive Manufacturing of Energetic Materials: An Overview

- Electrospray Deposition
- Inkjet Printing
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(Potential) Drawbacks of AMEM:

- Additional Interfaces
- Orthotropic Properties
- Known Challenges with Large Builds
- Unknown Throughput
- Existing Material Systems are Far from Optimized for Current Processes

Our Team (Faculty Leads)

Prof. Steve Son
- Energetic Materials
- Combustion Science

Prof. I. Emre Gunduz (*Naval Postgraduate School*)
- Material Science
- Material Processing

Prof. George Chiu
- Deposition Science
- Systems and Controls

Prof. Jeff Rhoads
- Energetic Material Physics
- Multiphysical Systems

Our Initiatives

1. Ink-Based Additive Manufacturing of Energetic and Reactive Materials
2. Filament-Based Additive Manufacturing of Energetic and Reactive Materials
3. Vibration-Assisted Printing of High-Viscosity Energetic and Reactive Materials

Our Initiatives

1

Ink-Based Additive Manufacturing of Energetic and Reactive Materials

2

Filament-Based Additive Manufacturing of Energetic and Reactive Materials

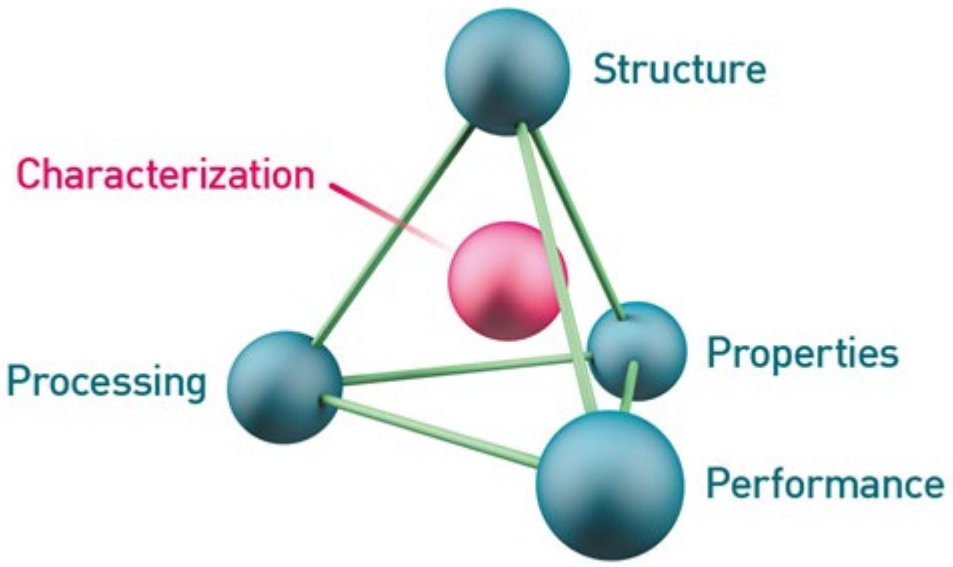
Today's Focus

3

Vibration-Assisted Printing of High-Viscosity Energetic and Reactive Materials

Project Focus

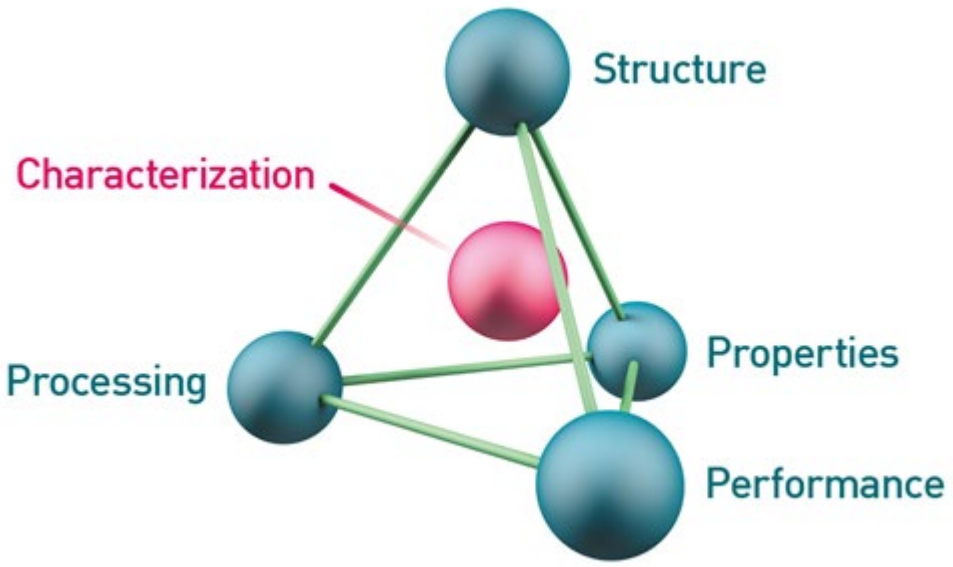
My Additive Manufacturing of Energetic Materials Worldview



From Malvern Panalytical (online)

To truly leverage the benefits of additively manufactured energetic materials (AMEM), we must understand the science underlying material-process-structure-function relationships.

My Additive Manufacturing of Energetic Materials Worldview



From Malvern Panalytical (online)

To truly leverage the benefits of additively manufactured energetic materials (AMEM), we must understand the science underlying material-process-structure-function relationships.

There are simply too many design "knobs" to rely on trial-and-error.

A Case Study: Filament-based AMEM

Technical Goal:

- Develop a reactive material system that was compatible with existing, low-cost 3D printers (e.g., a Makerbot).

Initial Focus:

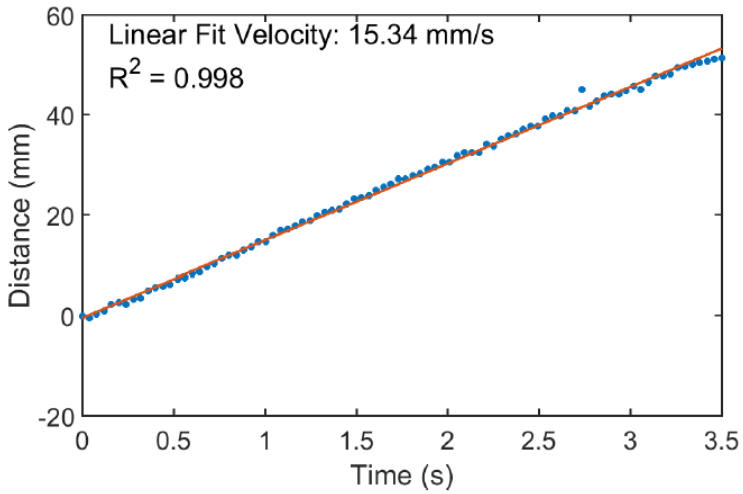
- Metal/fluoropolymer material systems (e.g., Al/PVDF)

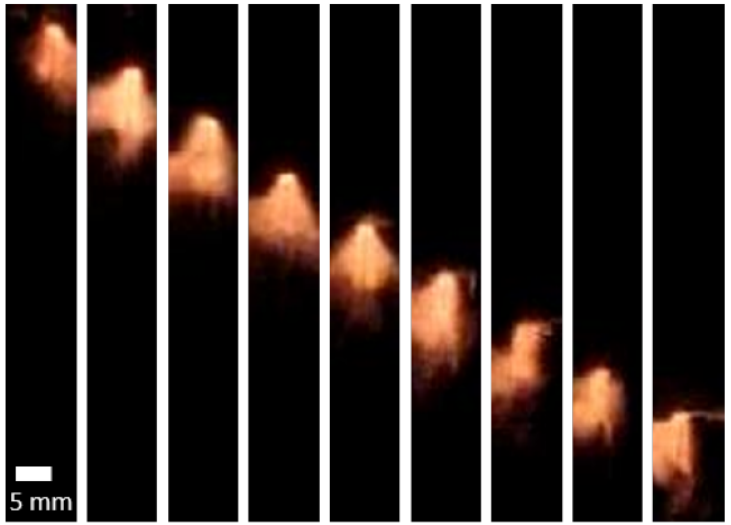
A Case Study: Filament-based AMEM

- In-house Processing
  - Synthesis
  - Pellet Formation
  - Extrusion (Filabot)
  - Printing (Makerbot/Monoprice)

- All processes controlled remotely as needed

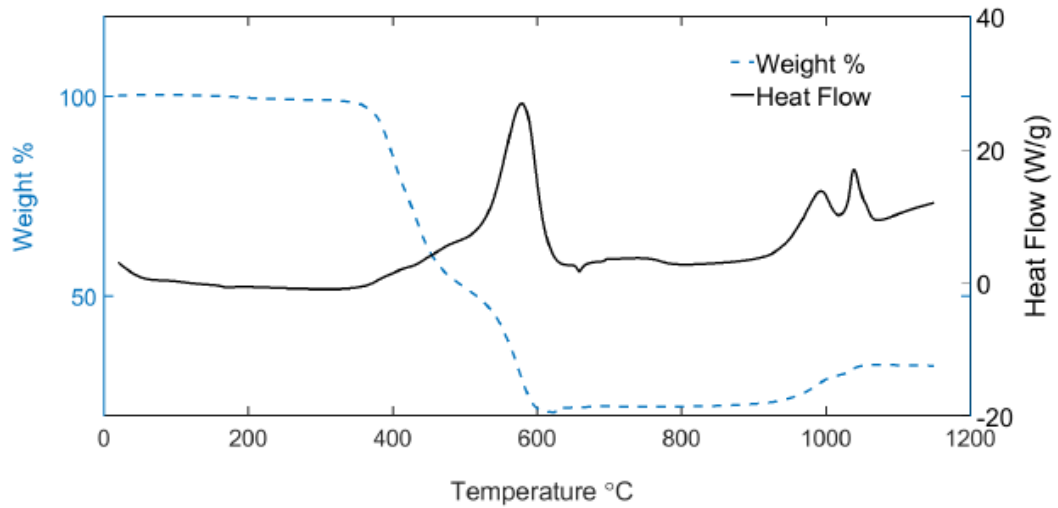
A Case Study: Filament-based AMEM

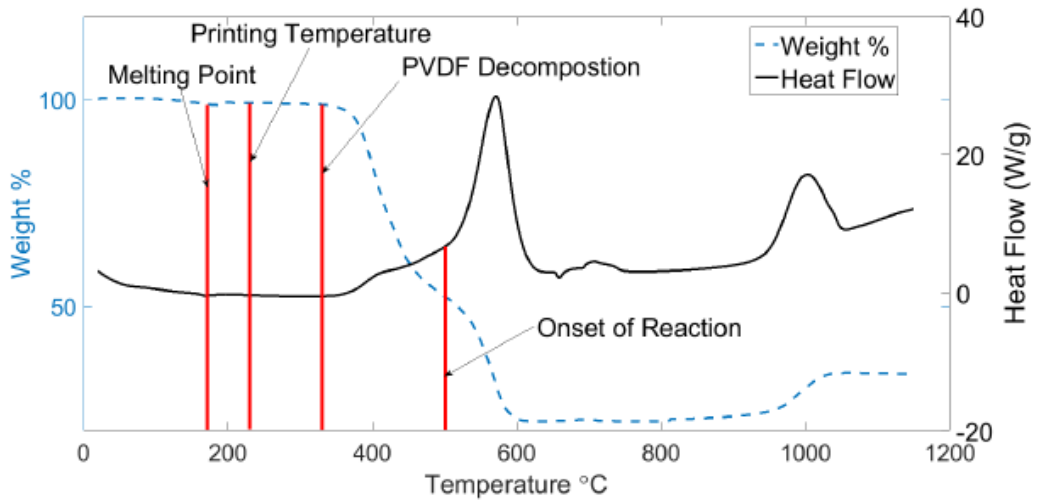




Slow Burning Gas/Solid Generator
(*at least with micron-sized aluminum*)

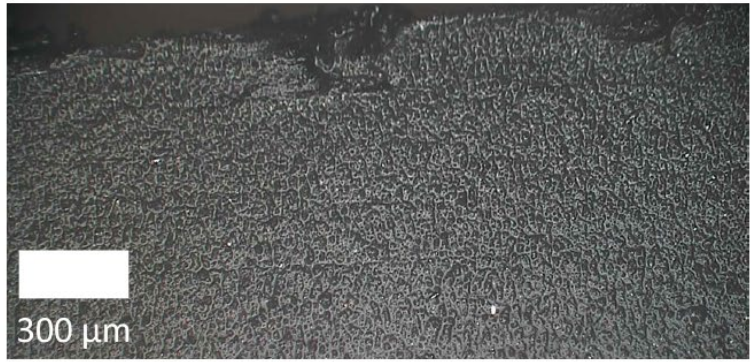
A Case Study: Filament-based AMEM

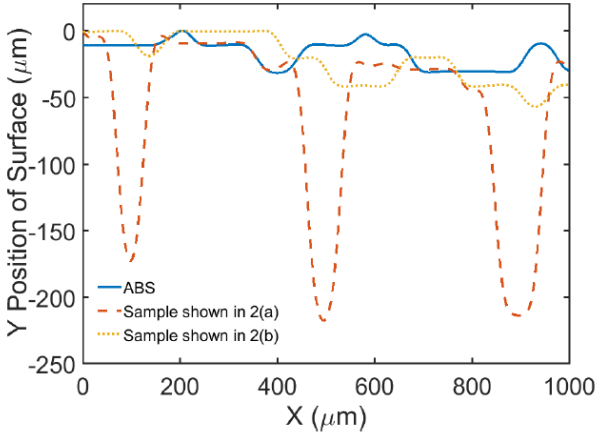




DSC/TG Analysis of Filament and Printed Wire

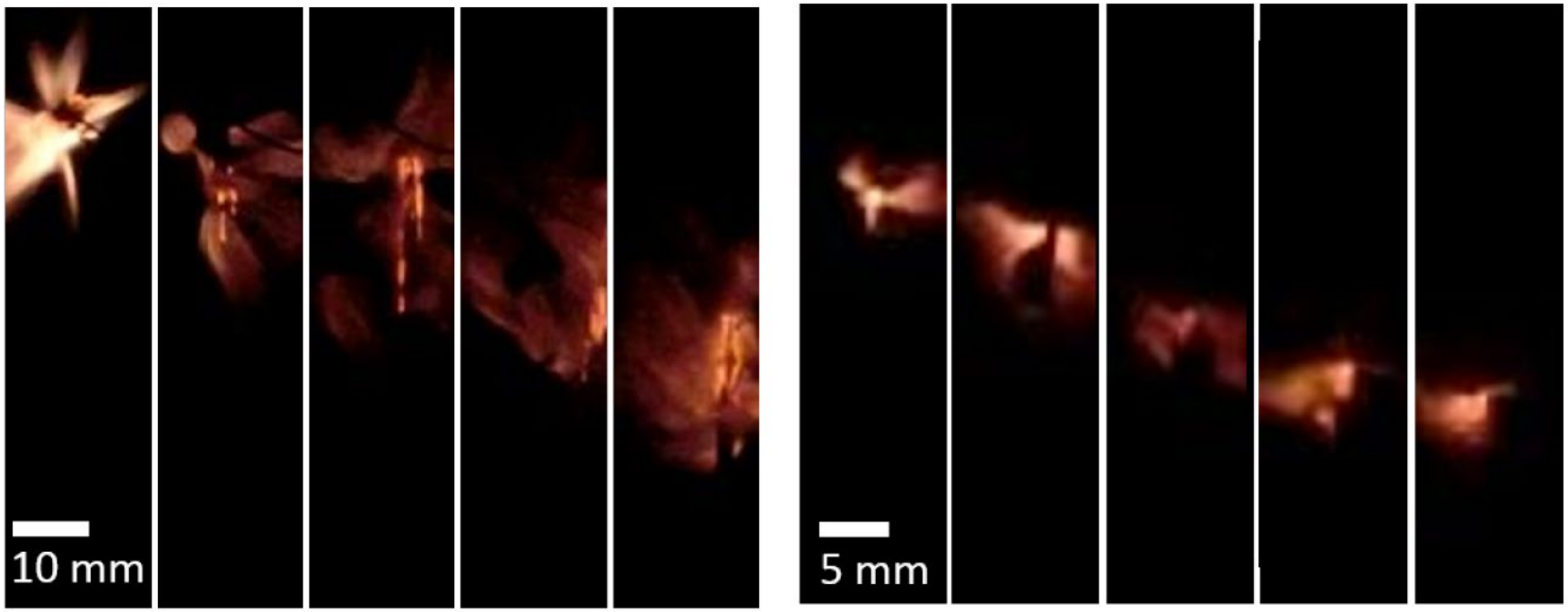
A Case Study: Filament-based AMEM





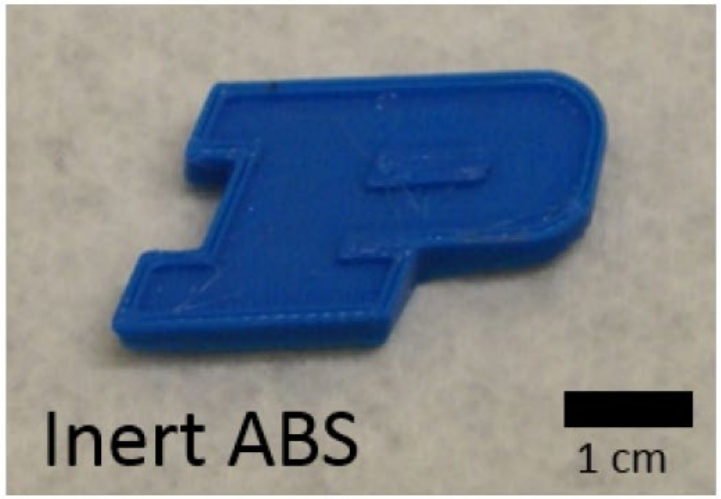
Technical Challenge in Print Setting Optimization

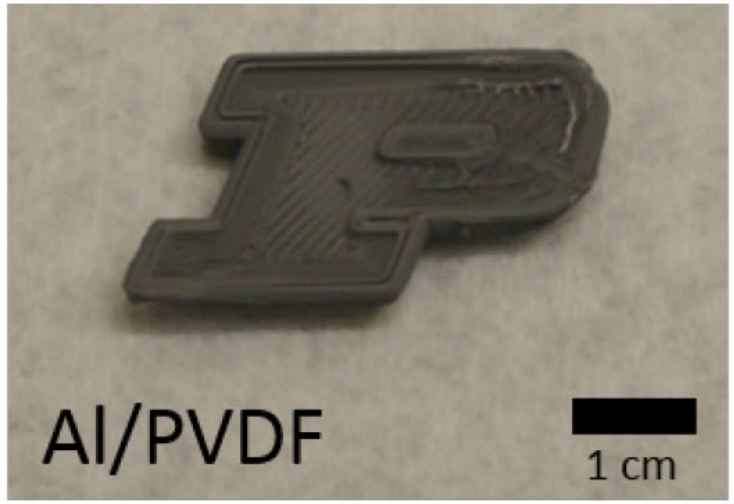
A Case Study: Filament-based AMEM



Tailored In-Fill Essential for Combustion Control

A Case Study: Filament-based AMEM





A Case Study: Filament-based AMEM

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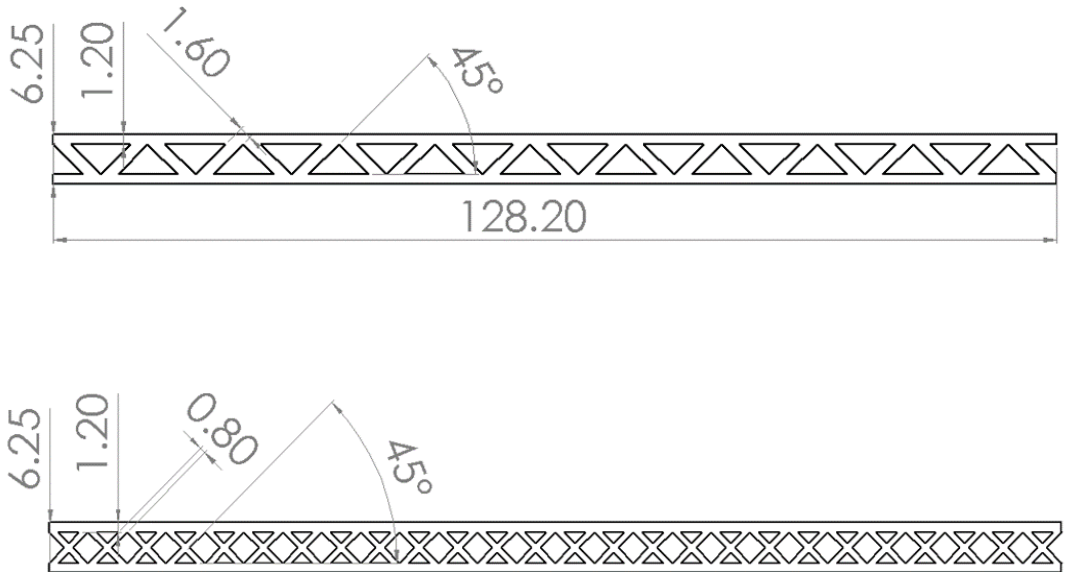
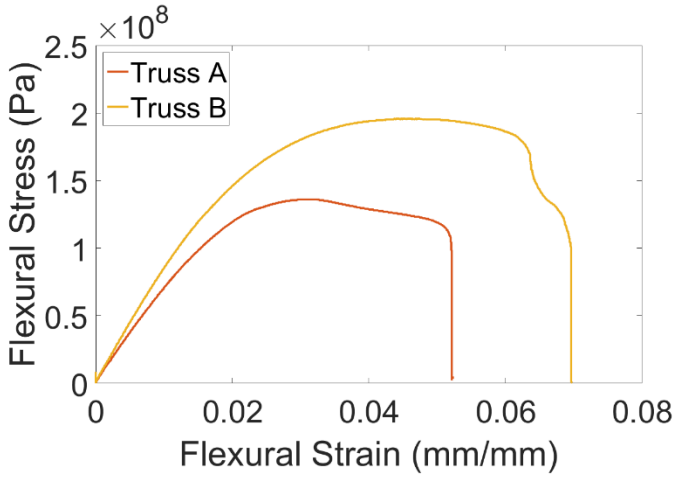
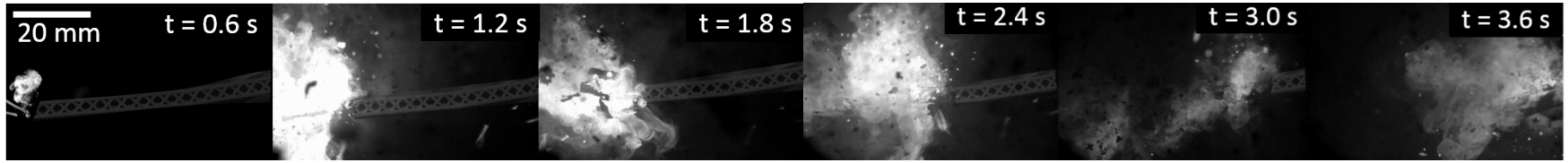
A Case Study: Filament-based AMEM







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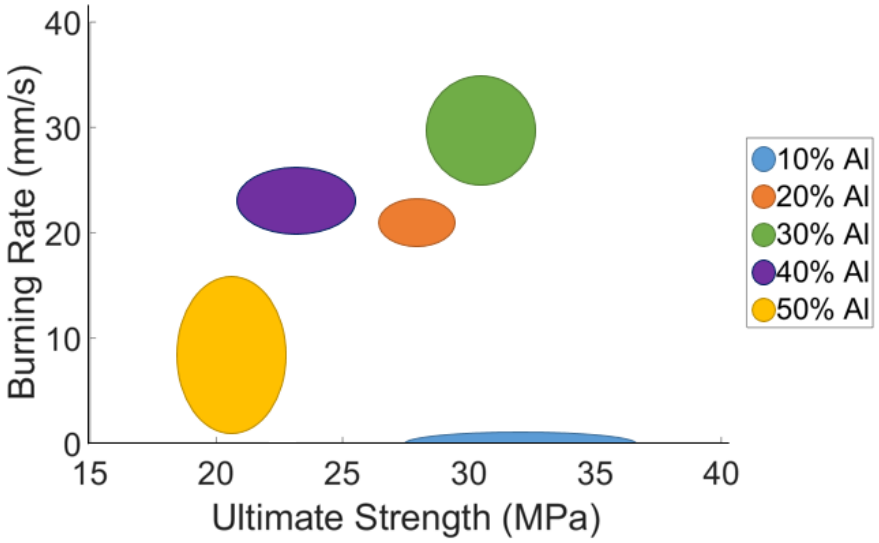

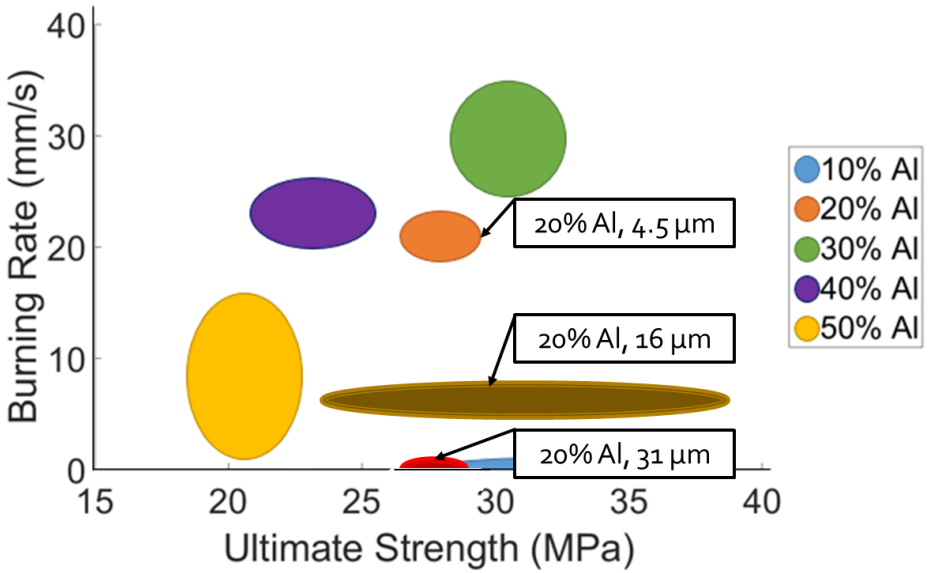

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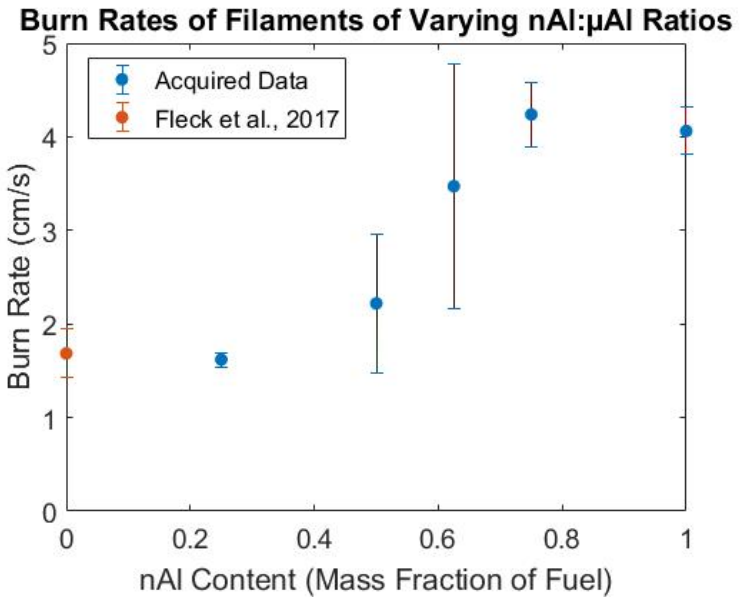
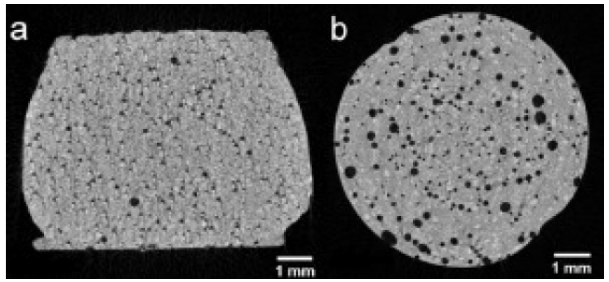
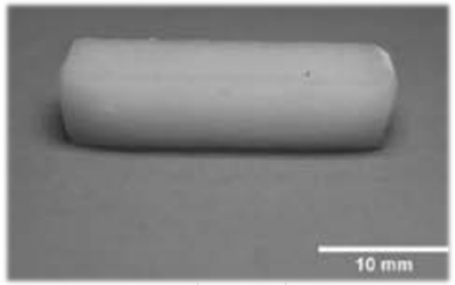


Burn Rates of Filaments of Varying nAl:µAl Ratios

Composition	*Batches*	*Sample Size per Batch*	*Average Diameter (mm)*	*Average Burn Rate** (mm/s)*	*St. Dev. (mm/s)*
nAl	1	6	1.51	40.6	2.5
3:1 nAl:µAl	3	7	1.56	42.4	3.5
5:3 nAl:µAl	3	7	1.60	34.7	13.0
1:1 nAl:µAl	3	7	1.56	22.2	7.5
1:3 nAl:µAl	1	7	1.55	16.2	0.8
µAl*	2	6	1.53	16.8	2.6

Moving Forward…





Fully Dense

Tailored

AP/HTPB Propellant Strands

Translate the playbook to explore the vibration-assisted printing of gun propellants.

Investigate material-process-structure-function mappings in ways that account for tangible costs, safety, and environmental impact.

Leverage *light* data science methods to identify useful parameter spaces, optimality is a secondary concern at best.

Acknowledgements

The many students and post-doctoral scholars who have assisted with this work, including Trevor Fleck and Diane Collard.

This material is based upon work supported by the United States Army Corps of Engineers under Contract No. W912HQ19C0063. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the United States Army Corps of Engineers.