AVT-340 Research Workshop on Preparation and Characterization of Energetic Materials

Gradient Printing of Energetic Materials

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- Why use AM for the production of Energetic Materials?
- History of AM of Energetic Materials at TNO
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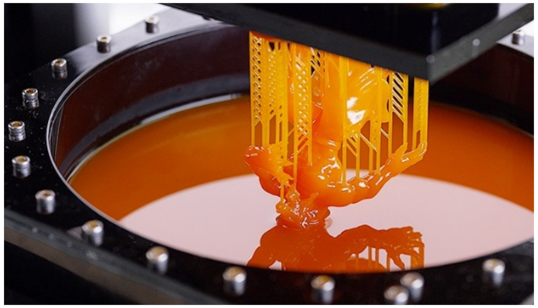
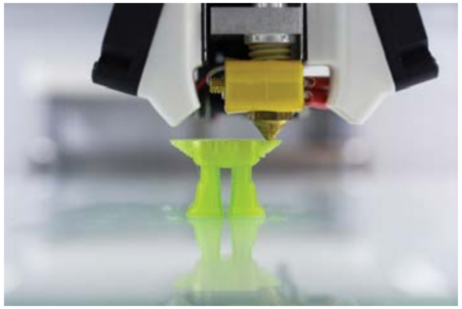
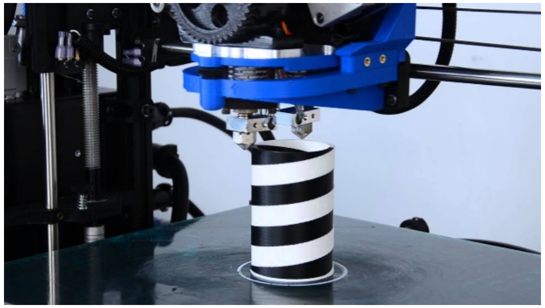
Introduction to Additive Manufacturing

- **Additive manufacturing (AM) is a collective name for several techniques through which products are built up in a layer by layer fashion. This has several advantages over conventional, often subtractive, production techniques:**
  - Less waste
  - Less geometric limitations (i.e. more design freedom)
  - The possibility to use unconventional material compositions
  - The possibility to combine multiple materials in a single manufacturing step

Why use AM for the production of EM?

- **Freedom of shape gives new possibilities to improve performance**
  - Solid rocket propellants
  - Explosives / warheads
  - Gun propellants
  - Pyrotechnics

- **Fine tuning burn or detonation properties**

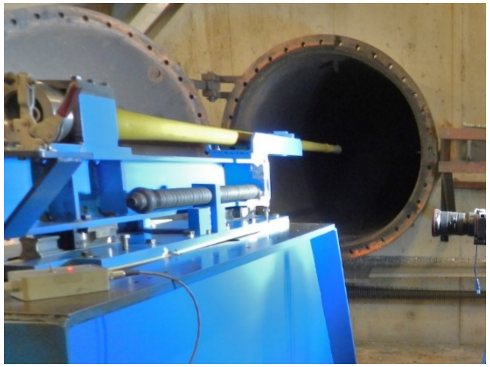
- **3D printing is an ‘enabling technology’ for future munitions (smarter, scalable, safer)**

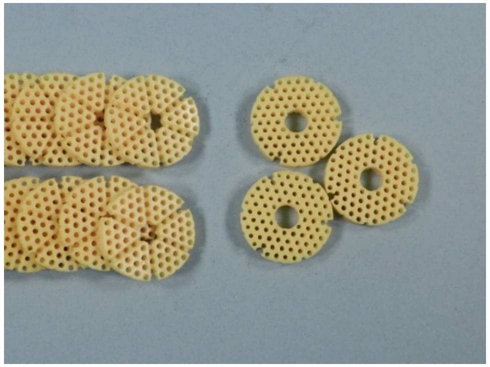
History of AM of EM at TNO

- **2013:** Exploration, TNT printed with FDM
- **2014:** First low energetic powders with SLA/DLP
- **2015:** High energetic powders with SLA/DLP and material optimisation
- **2016:** Reproducible printing powders and material characterisation and live firing
- **2017:** Development of higher solid load compositions, start of energetic filament development
- **2018-2019:** Printing of high solid load compositions, including gradients
- **2020:** Printing of first complete products with functional gradients

30 mm gun demonstration (2016)

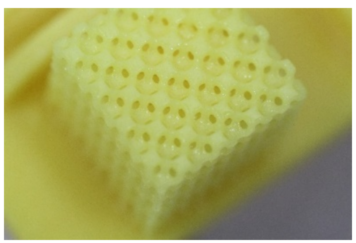
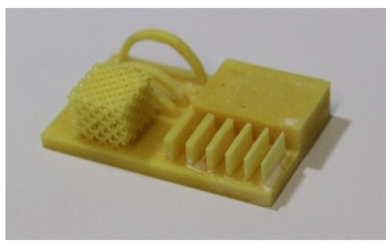
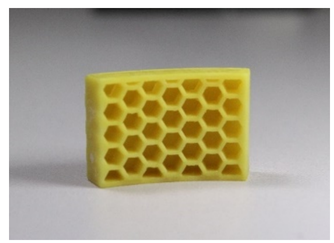
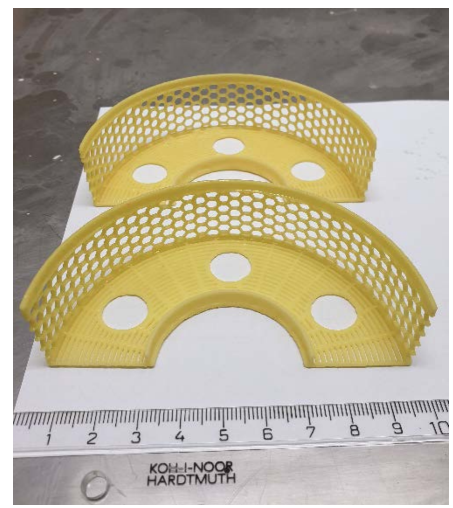
- 30 mm gun
- Results as calculated with internal ballistics
- No additional conventional powder added
- Printed on COTS digital light processing (DLP) printer

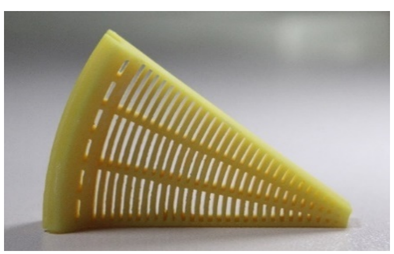
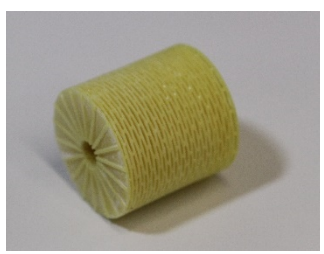
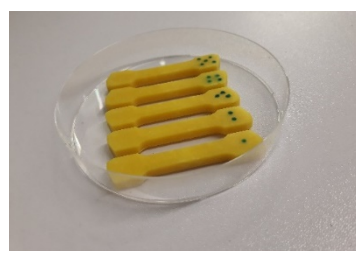





Further work with DLP

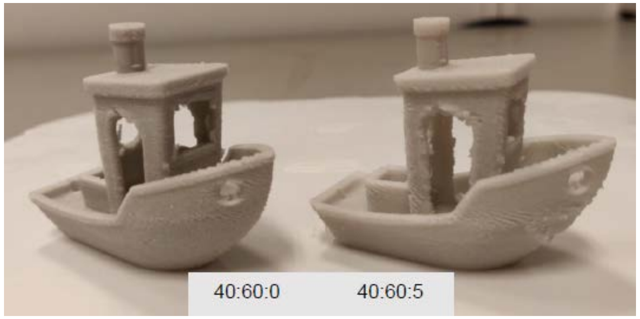
- Feasibility studies for several industrial (defense) partners
- Applications in specialty products
- Pushing the boundaries of geometry and resolution

Work on energetic filaments

- **Together with Dutch SME Senbis Polymer Innovations TNO developed a printable filament with a solid load of up to 80 wt%**
- **Melting point of binder should be low to safely print EM**
- **3D Benchy's were produced with 60 wt% solid load at 110 degrees C**
- **Inert simulant used instead of RDX**

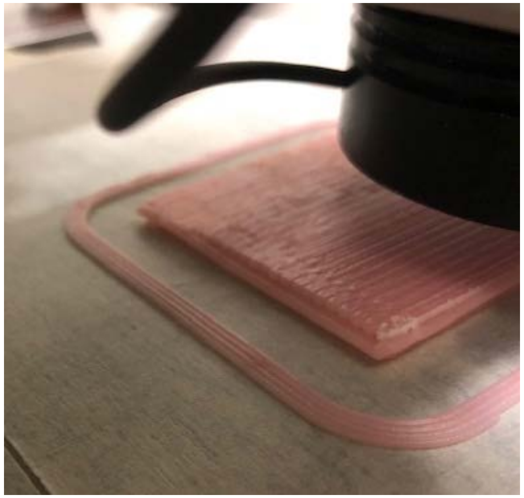


Development of gradient printer

- **No suitable COTS printer was found fulfilling safety and performance requirements**

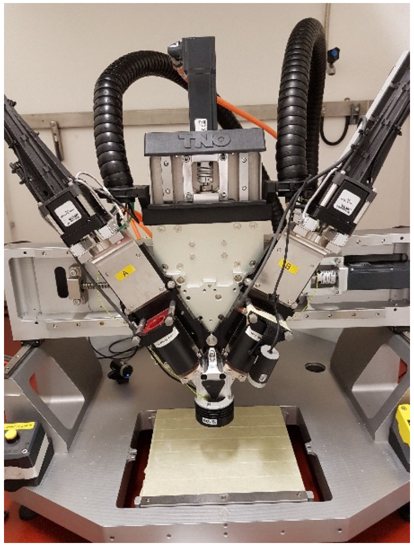
- **A printer was designed and built, based on existing TNO design, but heavily modified for EM safety**

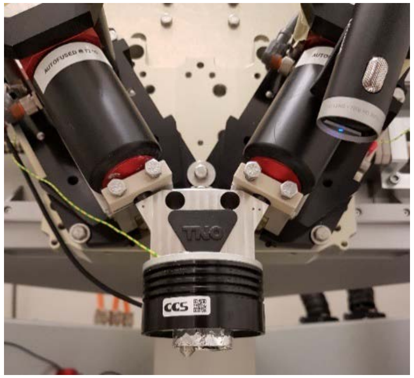
- **Required software and firmware were developed**
  - Extra safety features included in firmware/UI
  - Existing open source software package heavily modified to allow for the inclusion of continuous functional gradients



Development of gradient printer

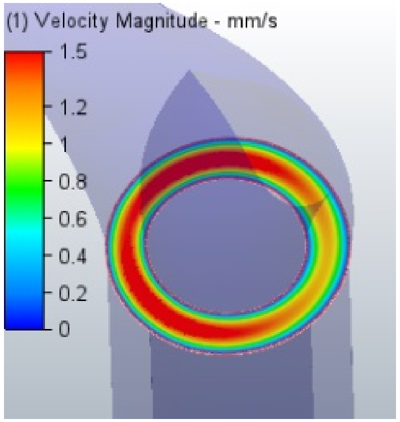
- **Large build volume (200 x 200 x 100 mm)**
- **Dual material feed**
- **Modular extruder configurations**
  - Single, double parallel, double V
- **Modular print head**
  - Parallel, Y, co-extruded
- **UV curing mechanism integrated in print head(s)**
- **EM safety features include**
  - Hard and soft limits on temperature and pressure
  - All parts anti-static or grounded
  - Potential leakage/contamination kept away from moving parts

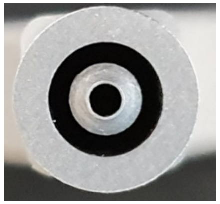


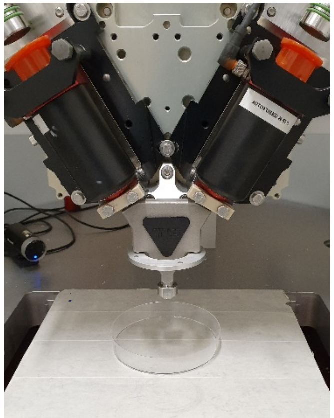


Development of gradient printer

- **Coaxial print head**
  - Combines two material feeds into core/shell filament
  - Merging region optimized for maximum concentricity and minimum pressure drop
  - Final product 3D printed from stainless steel, with minimal post-processing

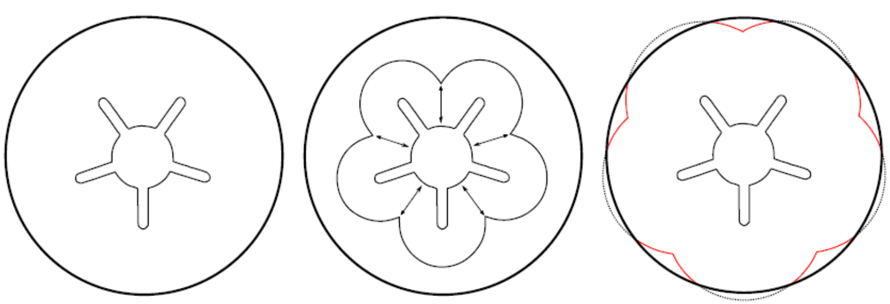


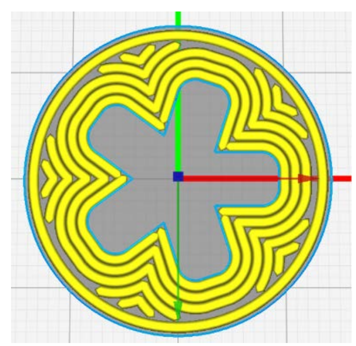


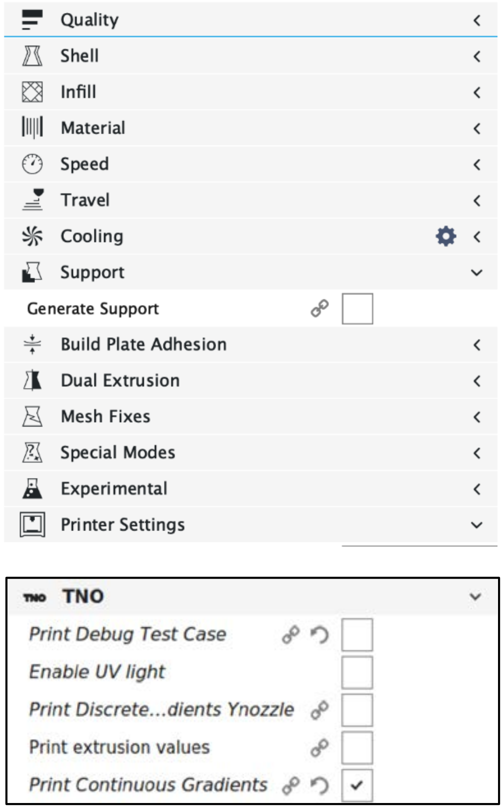


Printing software

- **Single material**
  - ➢ All standard options available
  - ➢ New infill patterns designed specifically for gun and rocket propellants
  - ➢ Translation to G-code dialect required by printer PLC

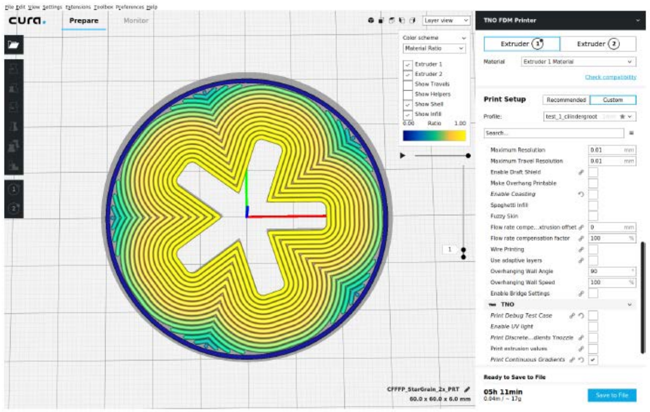


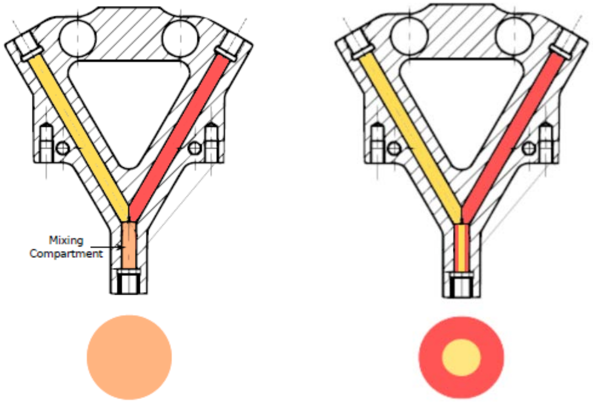


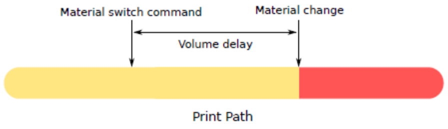


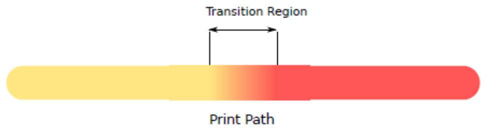
Printing software

- **Further software changes required for multi-material**
  - ➢ Cura does not have option for slicing (functionally) graded objects
  - ➢ User can now define a gradient function along the burn direction of the propellant (in tabular form)
  - ➢ Additional features, such as transition delay and a transition region have been included



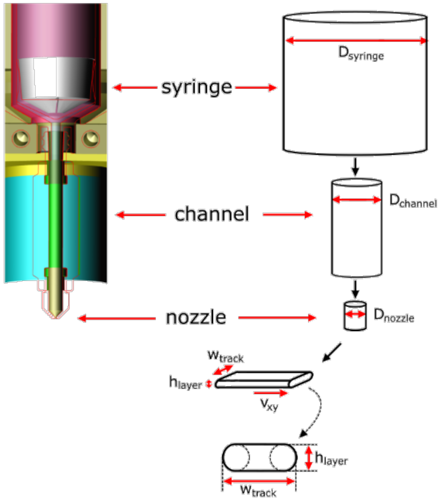


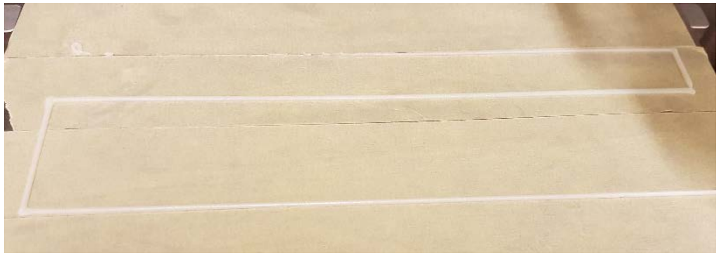




Deposition trials

- **Path deposition tests**
  - ➢ Three main printing parameters to be set:
    - ▪ Piston speed
    - ▪ Print head speed
    - ▪ Layer height
  - ➢ The extruded path width follows
  - ➢ In theory, the relationship between these parameters is fixed for incompressible fluids
  - ➢ In practice, effects like die-swell and shrinkage alter the relationship
  - ➢ Path deposition tests are used to characterize the relationship for each new material

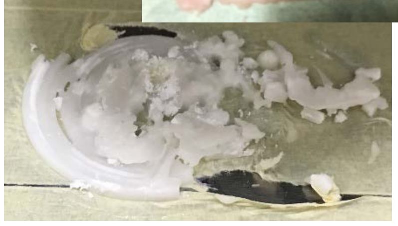




First print results

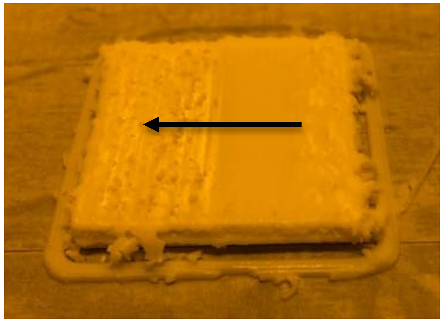
- **Single material print trials**
  - ➢ Fine-tuning of material printing properties
  - ➢ Initial assessment of achievable accuracy

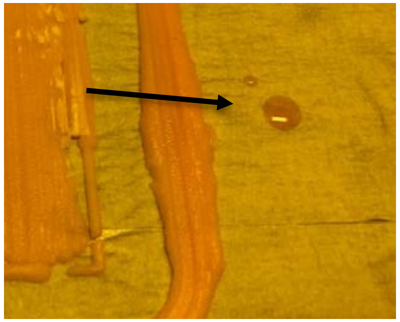



First print results

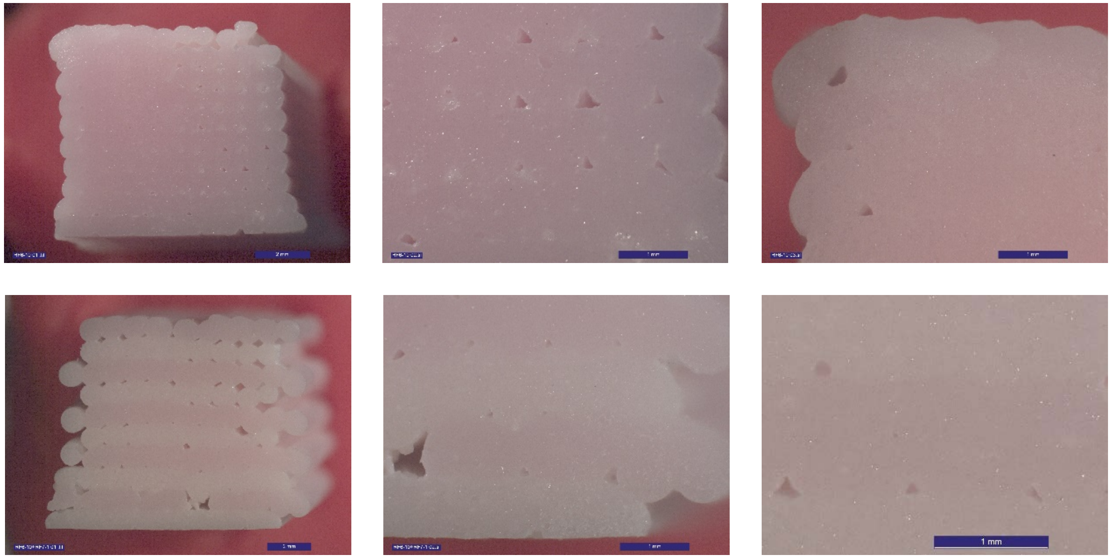
- **Challenges encountered when scaling up to larger items**
  - Problems seem to be related to extruding a larger percentage of the syringe
  - Most likely cause is demixing of the composition
  - The following solutions are being tried:
    - Changing the particle size distribution
    - Lowering extrusion pressure by using elevated syringe temperature (up to 60 degrees C)





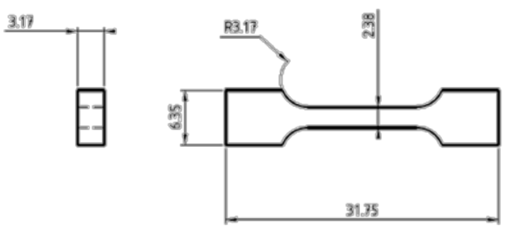
Analysis

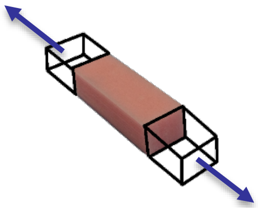
- **Microscopic analysis**
  - Analysis of inter-filament interfaces
  - Both single and dual material
  - No visual transition between deposited paths
  - Open channels between filaments need to be eliminated

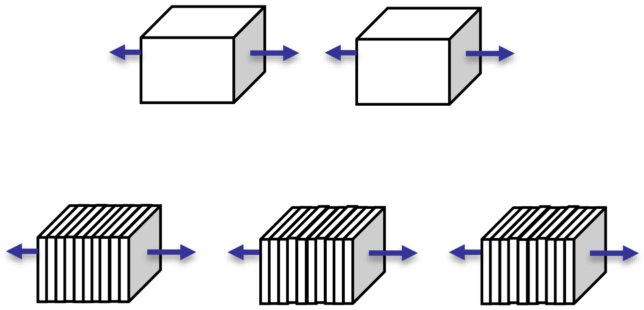


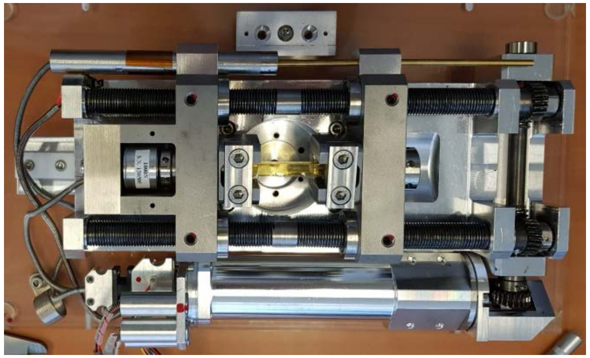
Analysis

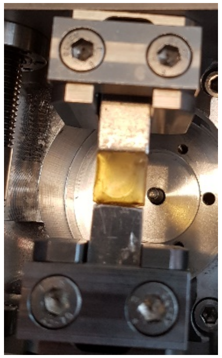
- **Tensile testing**
  - Specimens tested in micro-mechanical tensile testing device
  - ¼ JANNAF dog bone
  - Different configurations
  - Results still being analyzed





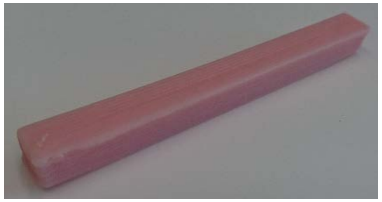
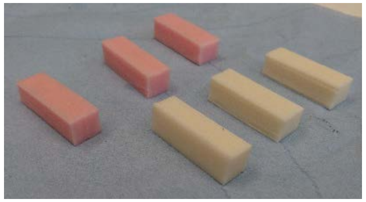
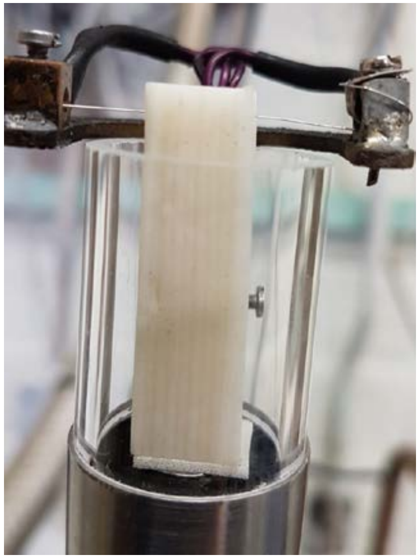






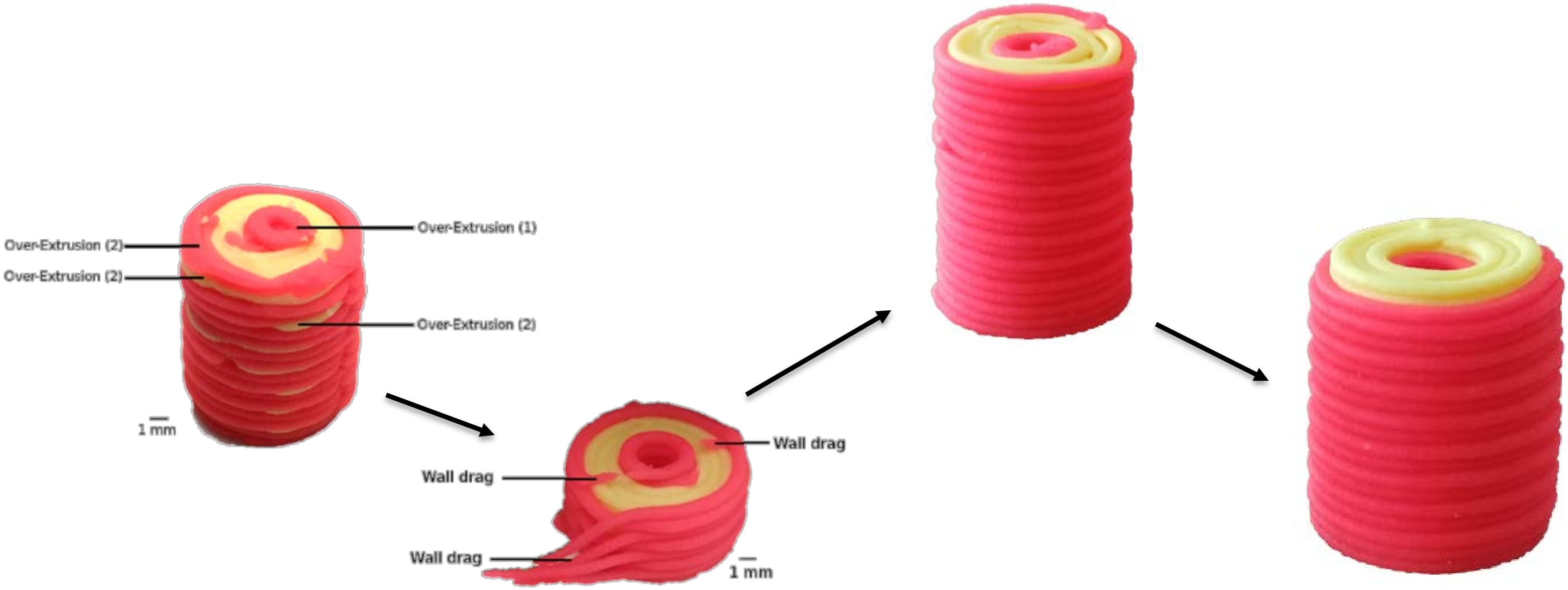
Analysis

- **Chimney burn testing**
  - Fast and slow burning compositions
    - 70 wt% solid load
    - 60 wt% solid load
  - Printed and manually prepared samples
  - Tested in N_2 flow under 40 bar
  - Ignition using hot wire

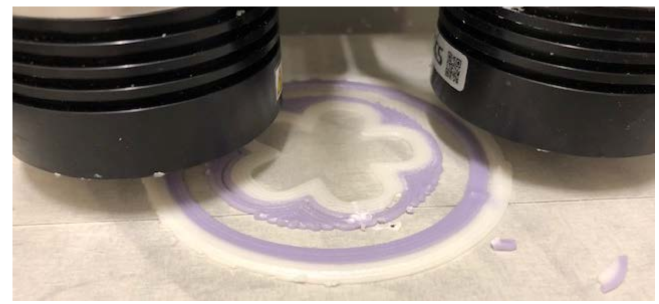

First gradient print results

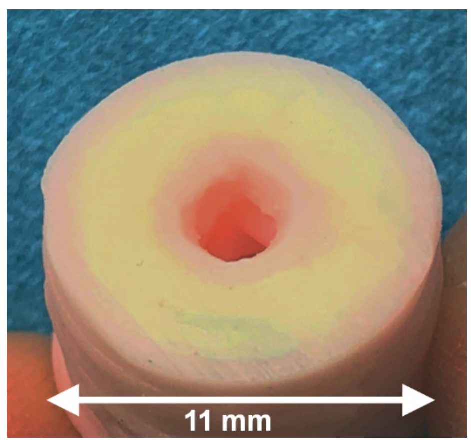
- **Discrete gradient printing trials**
  - Fine-tuning of process using inert simulants

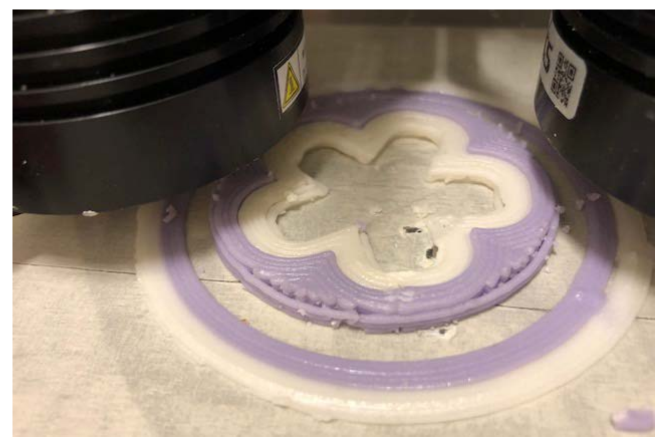


First gradient print results

- **Discrete gradient printing trials**
  - Switch to propellant compositions
  - Functionally different

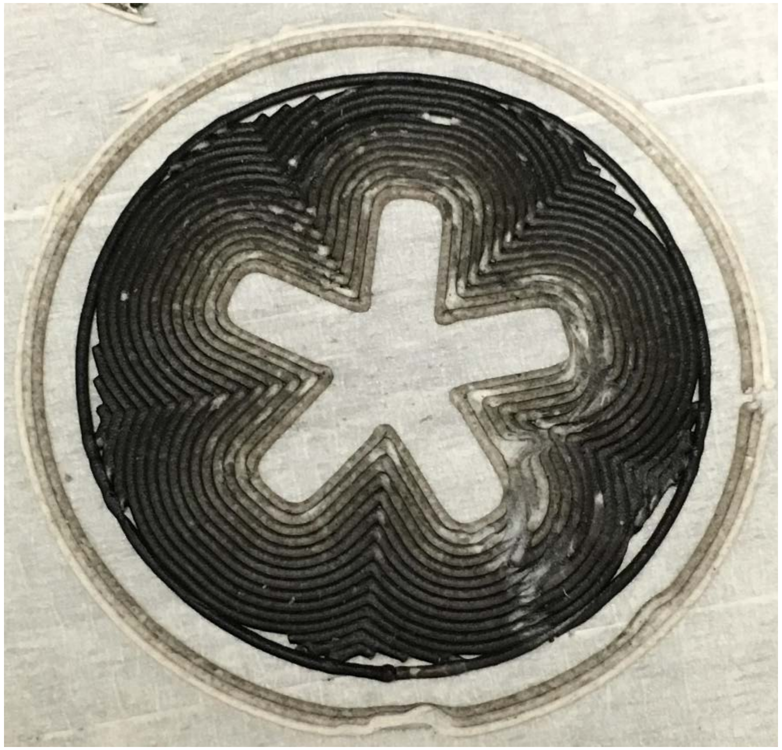






First gradient print results

- **Continuous gradient print trials**
  - Using co-extrusion print head
  - Using inert simulants



Future work

- **Printing of functionally graded energetic items, with focus on:**
  - Propellants
  - Explosives
- **Development of geometry optimization tools**
  - Design for AM
  - Include functional gradients
- **Continue energetic filament development with actual energetics**
- **Continue identifying specialties to print using DLP**

Acknowledgements

AFRL
THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

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AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

References

1. Straathof, M.H., Driel, C.A. van, Lingen, J.N.J. van, Ingenhut, B.L.J., Cate, T.A. ten, & Maalderink, H.H. (2020). Development of Propellant Compositions for Vat Photopolymerization Additive Manufacturing. *Propellants, Explosives, Pyrotechnics*, *45*(1), 36-52.
2. Straathof, M.H., Driel, C.A. van, Otter, J.A. den, Lingen, J.N.J. van, Heinsius, J., Isenia, J., & Rijnders, B. (2019). Gradient Printing of Energetic Materials – First Results. In V.K. Saraswat et al. (Eds.), *Proceedings of 31st International Symposium on Ballistics*, Vol. 1.