POLYMER AM AT THE KANSAS CITY NATIONAL SECURITY CAMPUS (KCNSC)

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MATERIALS COE LEAD

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Honeywell

National Nuclear Security Administration

KANSAS CITY NSC National Security Campus

The Department of Energy's Kansas City National Security Campus is operated and managed by Honeywell Federal Manufacturing & Technologies, LLC under contract number DE-NA0002839

Principal R&D Scientist – Materials Center of Excellence Leader
University of Southern Mississippi (Ph.D. polymer science & engineering)
St. Norbert College (BS chemistry)

KCNSC: 2013 – present
ORNL: 2004 – 2013

KANSAS CITY NATIONAL SECURITY CAMPUS

One Mission
One Ecosystem
Multiple Locations

Quick View

- A multi-mission engineering and manufacturing enterprise delivering trusted national security products and government services
- Department of Energy leased facility
- DOE National Nuclear Security Administration (NNSA) and DOE-IN oversight
- Managed & operated by Honeywell
- 5300+ employees
- $1.6B annual federal budget

Locations

- Botts Campus: 1.5M sq. ft. in 4 main buildings, including a 350K sq. ft. SCIF (Buildings 1-4)
- KCNSC South (Building 20)
- KCNSC West (Building 21)
- KCNSC North (Building 22)
- KCNSC East (Building 23)
- Albuquerque, NM: offices, 130k sq. ft. fabrication shop and vehicle depot facility

OUR MISSION

To support national security objectives by providing exceptional solutions, managed operations and targeted services through talented people.

NNSA MISSION PRIORITIES

SAFE, SECURE, EFFECTIVE DETERRENT

STRENGTHEN SCIENCE, TECHNOLOGY, ENGINEERING

MODERNIZE INFRASTRUCTURE

REDUCE GLOBAL THREATS / STRENGTHEN NSE

COHERENT ACTIONS TO SUPPORT

- Core Capabilities
- Smart Business Intelligence
- Key Partnerships
- Smart Facilities
- Early Stage Collaboration
- Workforce Pipeline
- Scale and Agility
- Supply Chain Resiliency
- Innovation – Technology – Science
- Enterprise and Community Integration

STOCKPILE STEWARDSHIP

OUTLINE

Background on Polymer AM at KCNSC

- A look back and early successes
- Approach to science-based manufacturing
- Polymer AM Consortium

Highlight research findings in the following areas:

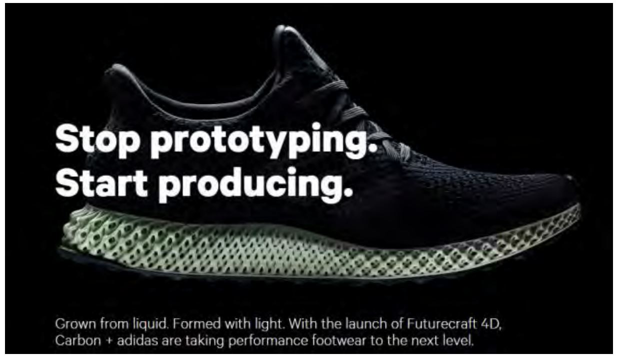
- High-temperature SLS development
- Performance improvements in thermoplastics for FDM
- Tunable silicone systems for DIW
- Rigid Syntactic Replacements
- “Smart” Materials for DIW

Conventional Polymer Manufacturing Issues

- Challenging to change product design…
  - Costly infrastructure (e.g., molds) and space needs
  - Scale-up from benchtop to large production
  - Some geometries are not accessible (topology optimization)
- Choice of polymeric materials
  - Limited selection of materials: conventional materials ≠ polymer AM materials
  - Current materials designed for current manufacturing processes (IM)
  - AM market is still small – custom materials development needed
- Advantages offered by AM over conventional methods:
  - Improved economics: less waste, reduced cost, reduced time to market, etc.
  - Mass customization: small #s of precision parts
  - High-strength structures (improved product quality)

Conventional injection molding equipment

http://www.log-imm.com/



http://www.carbon3d.com/

Need to Focus on Processes AND Materials

- Most 3D printing companies build printers and then try to adapt materials to fit those printers.
- Materials and machines can be tailored to meet the needs of the NSE.

POLYMER AM THEN & NOW

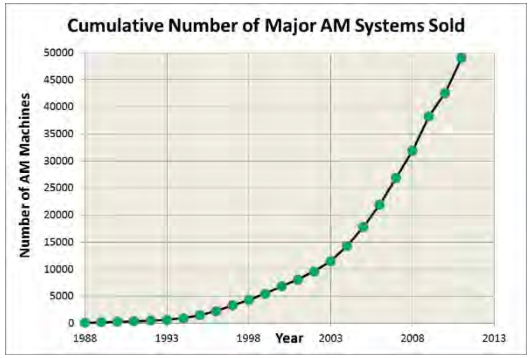
Then FY14

- Number of machines – 40+ (35 MakerBots)
  - Mostly desktop FDM systems, initial 3-axis DIW, "old-school" SLA systems…
  - Procured 35 printers in FY14 and 'they are not only changing the Paradigm, but saved another $6.4M in the first part of FY14 printing over 5,000 development parts, tools, and fixtures."
- Number of printable polymers available ~ 20
  - Discussions with polymer suppliers (e.g., Bayer Material Sciences/Covestro) at ACS National Meeting – "no real market for polymer AM"
- Number of insertions
  - **What was inserted/numbers of parts, etc.**

W88Alt 370 Pads

- Primary use: tooling & fixtures, prototypes
- Technical Successes
  - **Changed way of thinking about manufacturing,**
  - **Started to think about using topology optimization**
  - **Realization that DIW silicone pads could be modelled (compared to stochastic foams – CS/RTV), ability to quickly make visual displays/prototypes**

MakerBot Replicator 2X



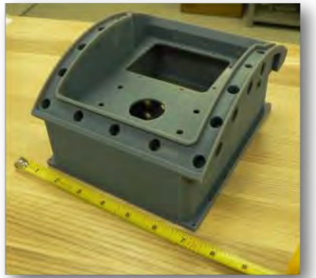
Source: Wohlers Report 2012

Stratasys Fortus 900mc installed February 2014

CONNEX500 SYSTEM

What to use it for:

- Prototypes
- Visual Displays
- Fixtures
- Molds
- End use items



Rigid Opaque

Transparent

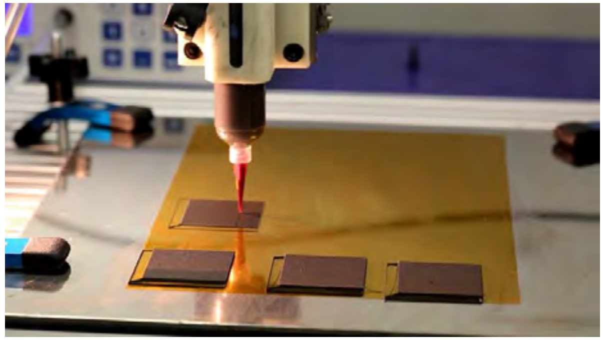
Flexible

Moving Assemblies

POLYMER AM THEN & NOW

Now FY19/FY20

- Number of machines – 60+
  - R&D efforts and printers at university collaborators
  - Multiple 5-axis DIW systems in production (M-90) and R&D
- Number of printable polymers available > 100
- Primary use: *WR product*, mocks, fixtures, prototypes, initial mold designs
- Technical Successes
  - Polymer AM Consortium, AM facility, ACE facility, multi-site ACT project (AM Thermosets), improved understanding of process-structure-property relationships (science-based mfg), materials development with vendors (Solvay, ALM), custom formulations
- Technical Opportunities
  - Accelerated aging/compatibility
- What's around the corner?
  - Microstereolithography, foams, thermosets/rigid syntactics, custom AM feedstock facility (filaments and powders), multi-functional materials/sensors



Direct Ink Writing of novel inks

High-temperature SLS capabilities: Prodways HT2000 at Virginia Tech (left) and EOS-NA P400 at KCNSC (right)

POLYMER AM FACILITY (DEPARTMENT M-90)

EOS P450 Installed in M-90

Thanks to Nick Green

KCNSC's Science Based Manufacturing Approach

Internal

Fundamental & applied R&D, deployment/insertion

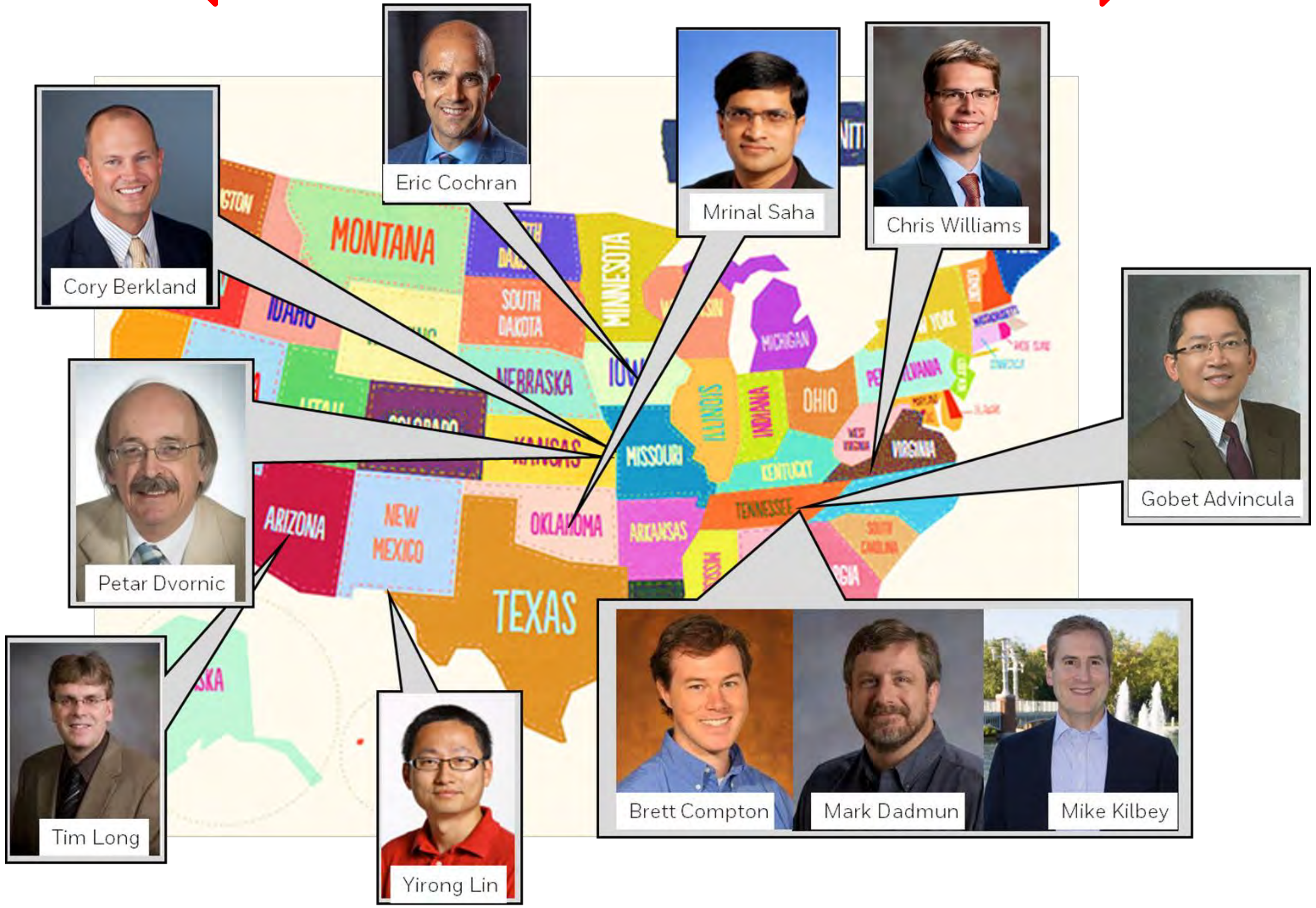
Low TRL: develop concepts & ideas with collaborators: university & National Lab partners

High TRL: on-board technologies at KCNSC

External

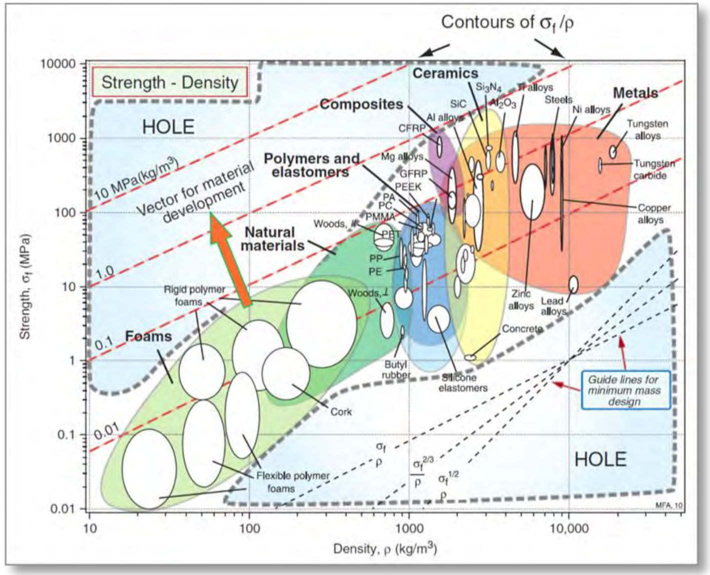
Fundamental/basic R&D

Polymer AM Consortium
Academic Partners

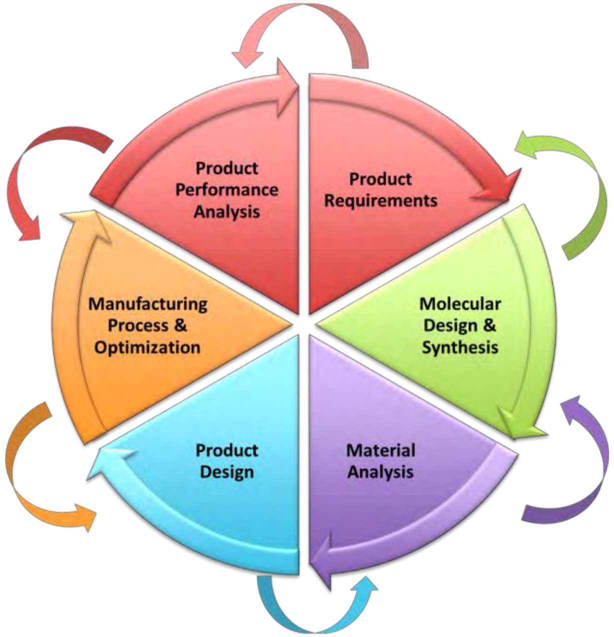


Polymer AM Consortium Goals

- Fundamental understanding of AM processes
  - Develop science-based approach to materials development and machine parameter selection: improve materials, AM processes, and enhance critical material properties to improve processing, performance, lifetime (aging), and safety
- Develop a catalog of the “right” materials for use in NNSA applications
  - Currently available commercial materials are “repurposed” – originally designed for traditional manufacturing methods (e.g., injection molding)
- Create a pipeline of talent – hire next-generation of scientists/engineers



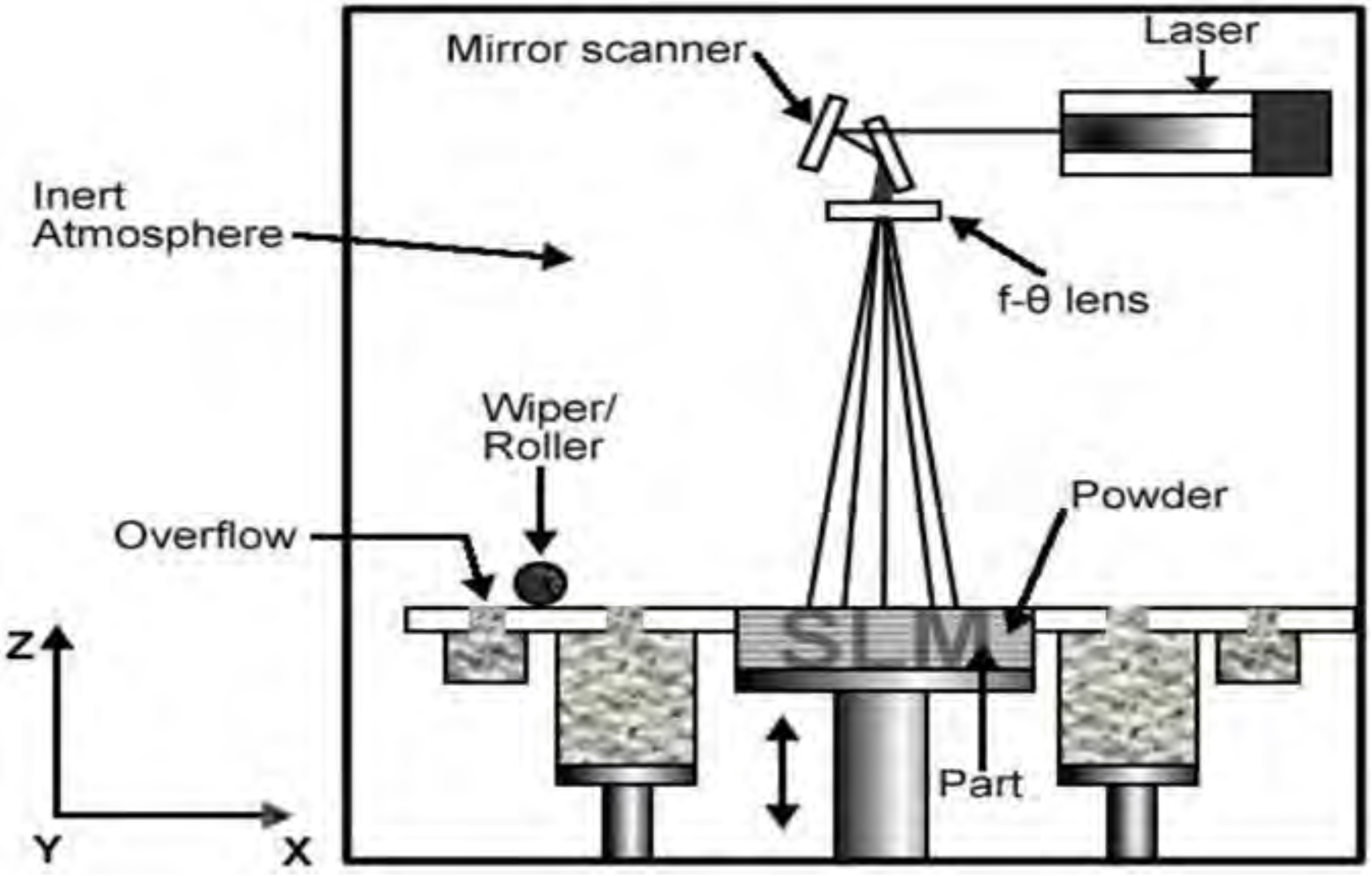
Typical Ashby plot correlating strength and density



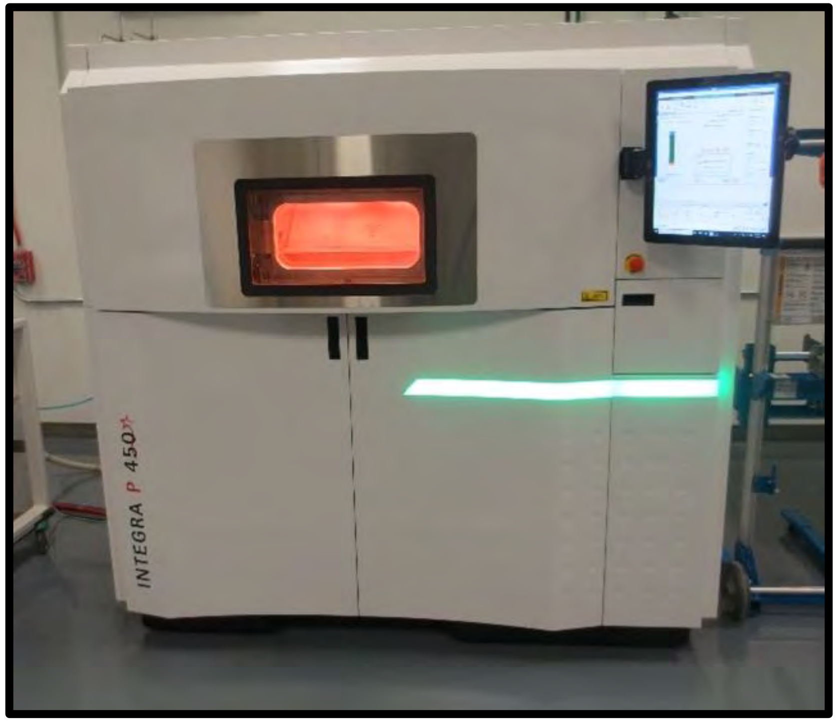
Opportunity to realize breakthrough products via ***concurrent design*** of ***polymer chemistry***, ***part geometry***, and ***manufacturing process***

Selective Laser Sintering (SLS)

Technology Overview



SLS Equipment/Capabilities



EOS P450 Series, High Temp Capable, KCNSC

Other Machines:
- Prodways HT2000 – Virginia Tech
- DTM Sinterstation 2500+ – Virginia Tech
- Custom Benchtop System – University of Oklahoma
- EOS P110 - KCNSC

https://natubots.com/vit-sls/?lang=en

https://www.sinterit.com/sinterit-lisa-pro/

VIT/Sinterit Open Source Benchtop Systems, University Partners

https://www.eos.info/en/additive-manufacturing/3d-printing-plastic/eos-polymer-systems/eos-p-396

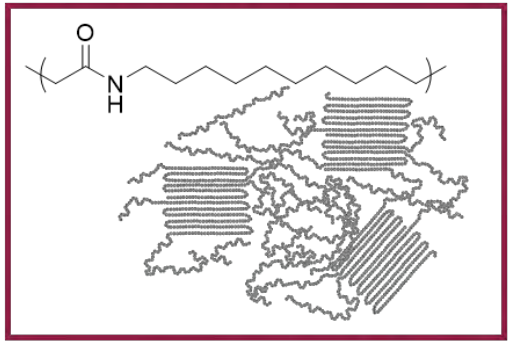
EOS P395/P396, PA12 Workhorse, KCNSC

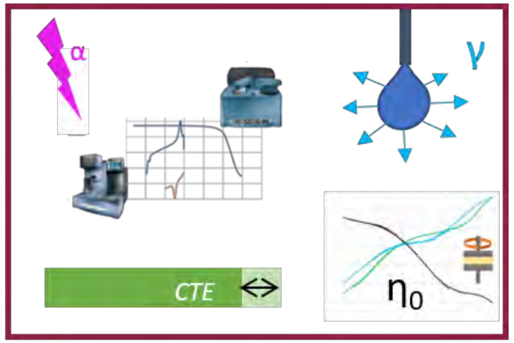
Pallmann Industries Cryomill, KCNSC

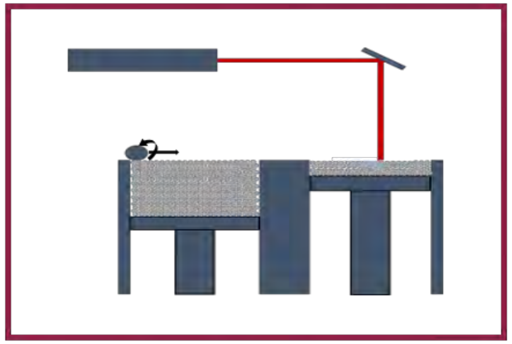
NNSA · Kansas City National Security Campus · Honeywell

Science-Based Manufacturing for SLS

PRINTABILITY TRIAD







chemical and morphological
Structure
of input material

define

intrinsic polymer
& extrinsic powder
Properties

that enable

Processing
through a set of
governing physics

Processing
at a given set of conditions

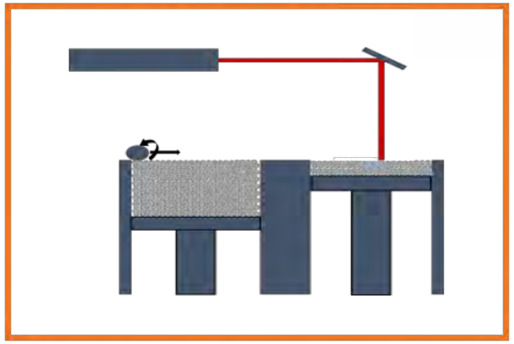
creates

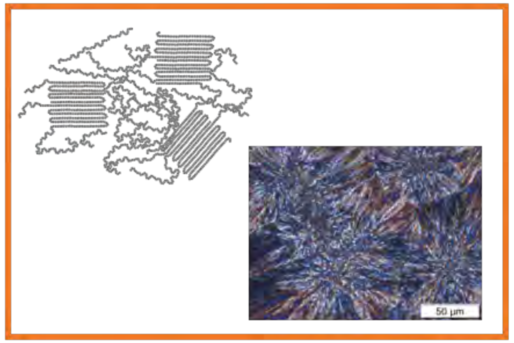
particular
Structure
on the microscale and
mesoscale

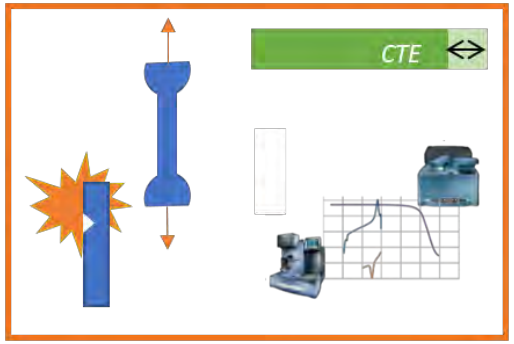
resulting in

Properties
of manufactured parts

PRINTED PARTS TRIAD







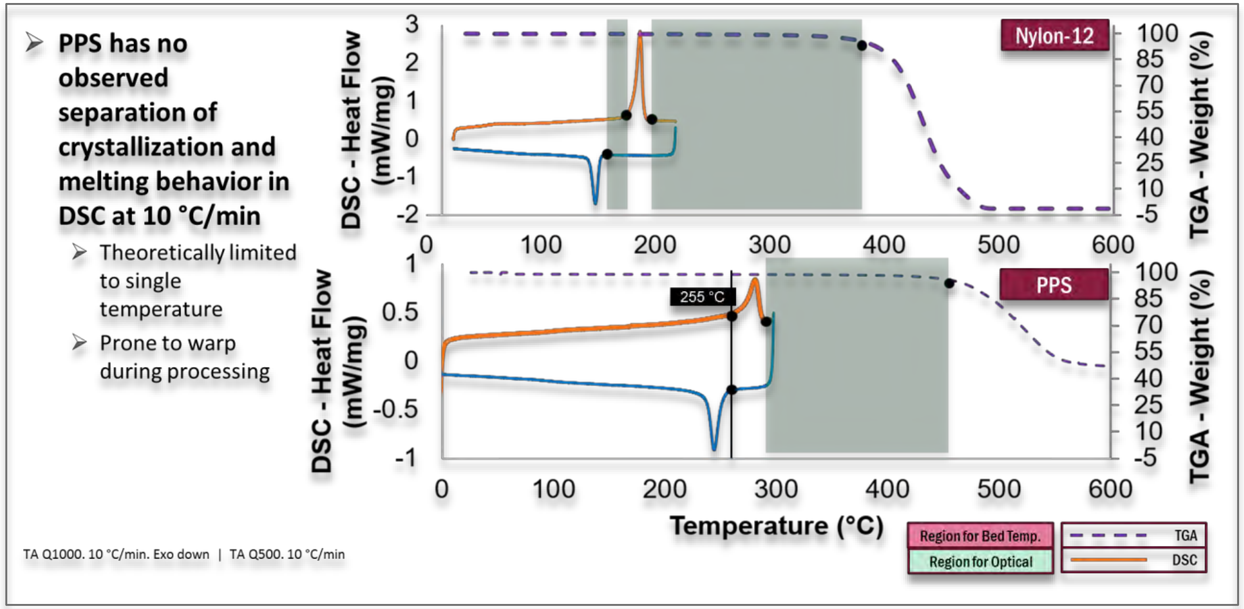
Thanks to Virginia Tech

RAPID DEVELOPMENT OF THE "RIGHT" MATERIALS FOR 3D PRINTING

Target application: potting shells & dams

- Material that surrounds electrical connections that is "set in place" with polyurethane potting compounds
- Currently made via injection molding
- Strong desire to move to a science-based manufacturing approach: understand structure-property-process relationships
- Worked with supplier (Solvay) to get correct MW, particle size, etc.

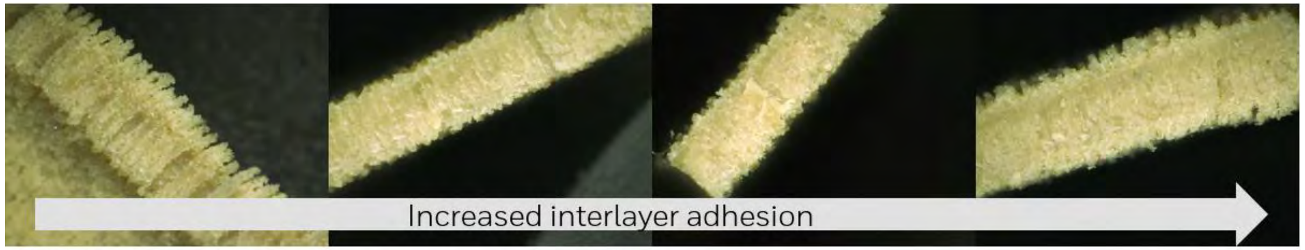
Establishing fundamental understanding of thermal properties (PA-12 vs. PPS) for printing – Stable Sintering Region:

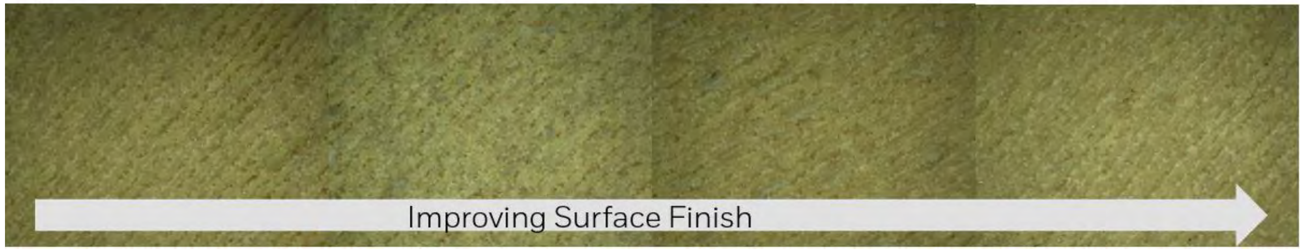


Progression of PPS Printing

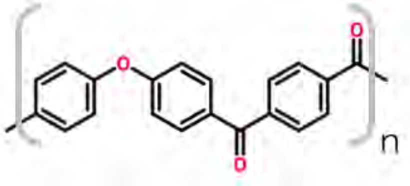
3D PRINTING OF PAEKS AND PEI

- Why Poly Aryl Ether Ketones (PAEKs)?
  - Desirable dielectric properties
  - Excellent chemical resistance
  - Excellent thermal properties
- Selective Laser Sintering of Poly(Ether Ketone Ketone) PEKK
  - Utilize high-temp SLS system, the EOS Integra P450
  - Prints successful on first attempt – utilized methodology developed to intuitively select parameters based on polymeric structure

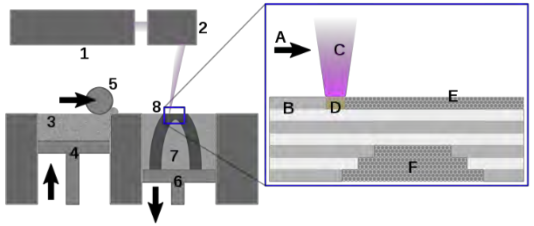




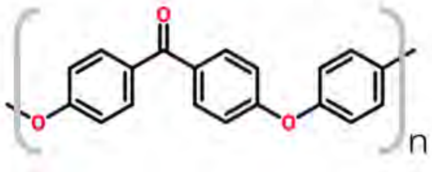
The combination of build temperature, hatch laser power, and contour laser power is important to optimize both interlayer adhesion and part finish.



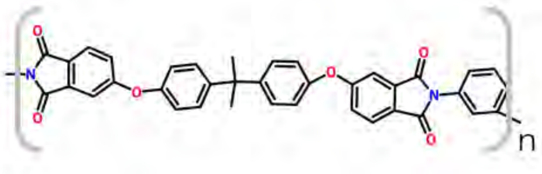
PEKK Chemical Structure



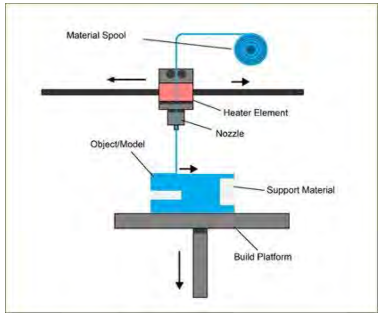
Selective Laser Sintering (SLS)



PEEK Chemical Structure



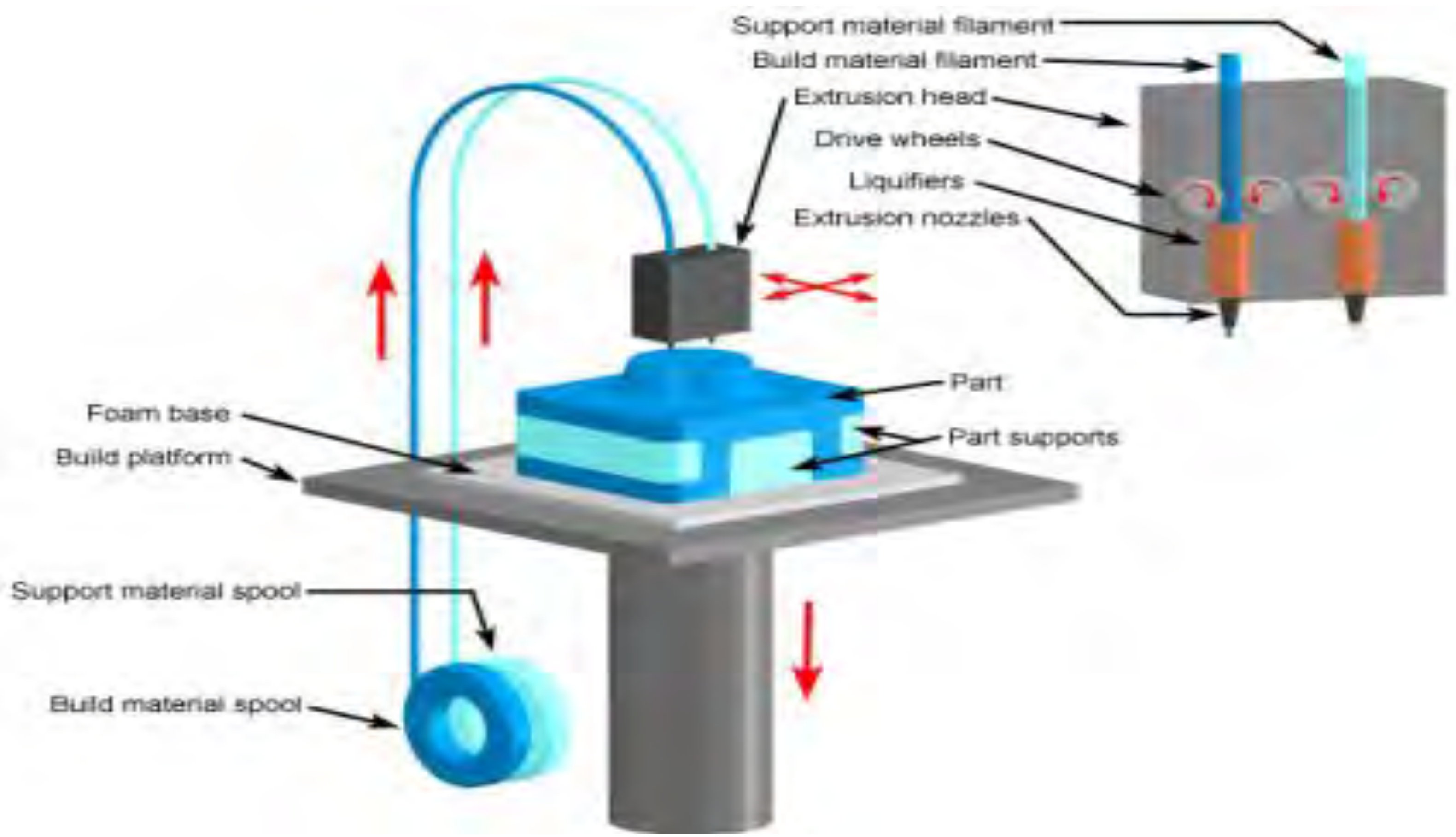
PEI Chemical Structure



Fused Deposition Modeling (FDM)

Fused Filament Fabrication (FFF)

Technology Overview



FDM Equipment/Capabilities

https://www.aon3d.com/aon-m2-2020-industrial-3d-printer/

AON-M2 HT Capable, Open Source, KCNSC

https://dyzedesign.com/pulsar-pellet-extruder/

Dyze Designs Pellet Extruder, KCNSC

Intamsys Funmat HT, Benchtop, KCNSC & University Partners

https://www.thermofisher.com/order/catalog/product/567-7600#/567-7600

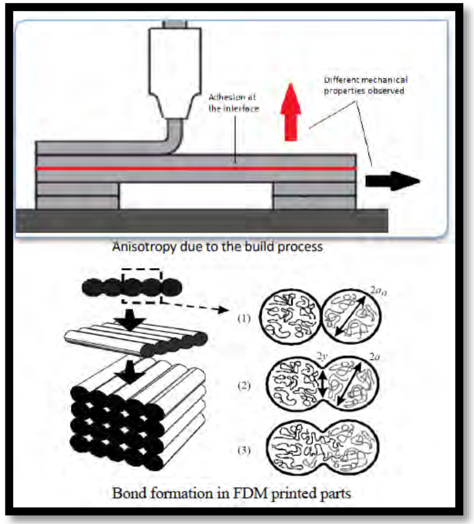
Thermo Scientific Process 11 Twin Screw Extruder, KCNSC

https://www.stratasys.com/3d-printers/fortus-380mc-450mc

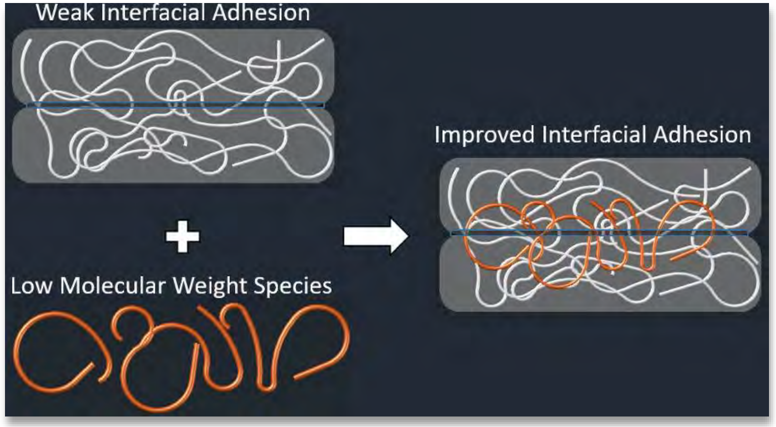
Fortus 450mc, KCNSC

Other Machines:
- **Makerbots**
- **Lulzbot – University of Tennessee – Knoxville**
- **Custom benchtop systems – OU, Virginia Tech**
- **Filabot – multiple universities**

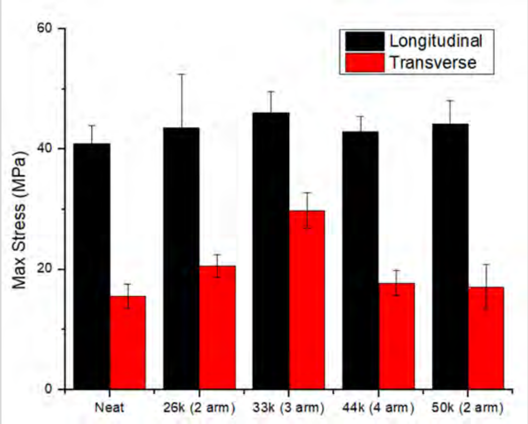
Improving Isotropy Through a Low Molecular Weight Surface Segregating Additive for FDM



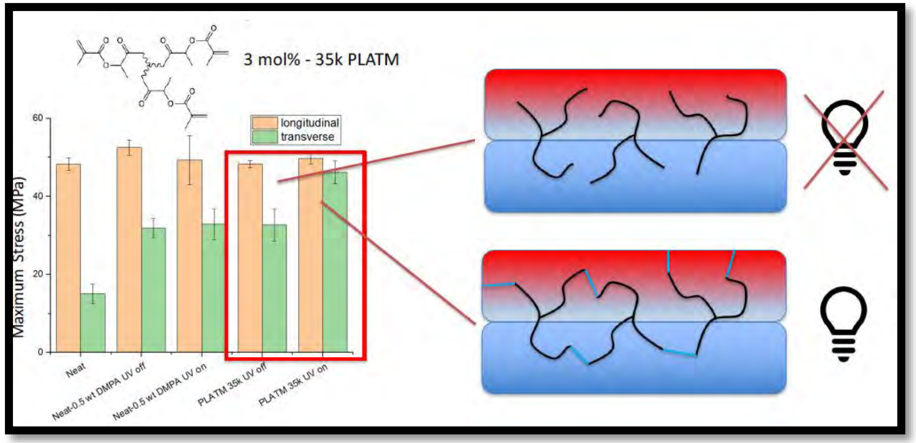
- Aiding inter-filament bonding via molecular assembly
- Small polymer chains diffuse faster than large chains
- Entropically driven to the interface
- *Increased* inter-filament diffusion and stronger interfaces
- Target MW → Greater the M_e, less than majority filament
- Create bimodal blends
  - Low molecular weights (LMW), loadings, chain architectures

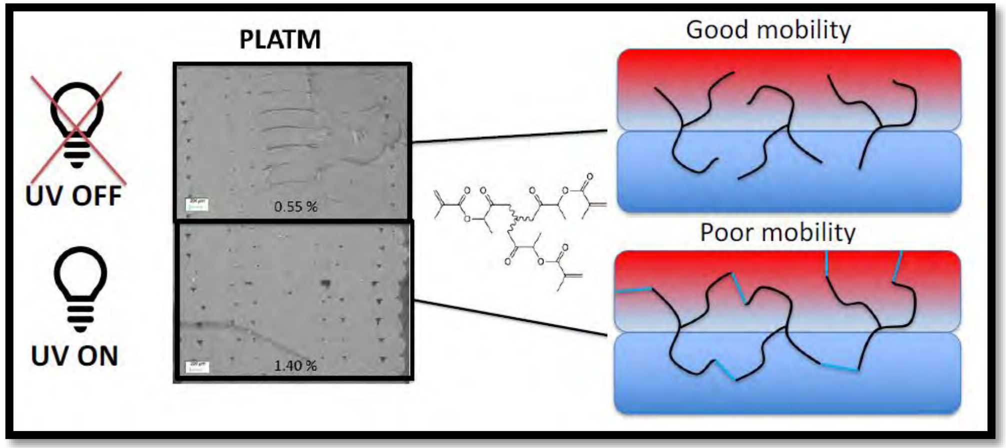


Mechanical properties in transverse (red) and longitudinal (black) orientations



Polymer **2017**, *122*, 232-241
Polymer **2018**, *152*, 35-41





- UV initiator + LMW additives enables inter-filament crosslinks
- Key to find balance between improved crosslinking and limitation of chain mobility (UV intensity) – reduction of void size

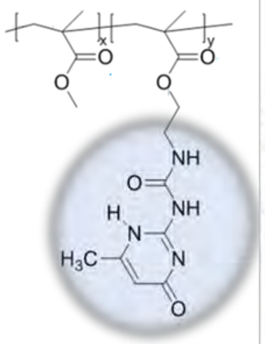
Thanks to the University of Tennessee

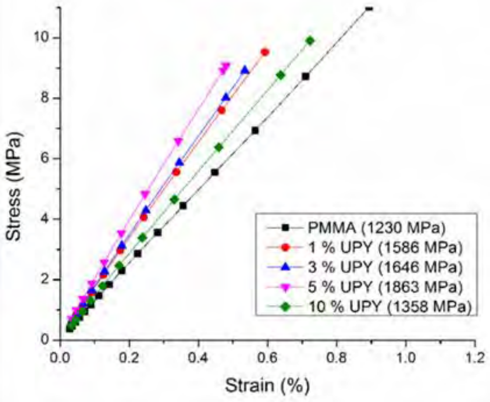
Hydrogen-bonding Motifs Attached to Nanoparticle Fillers Dramatically Enhance Mechanical Properties

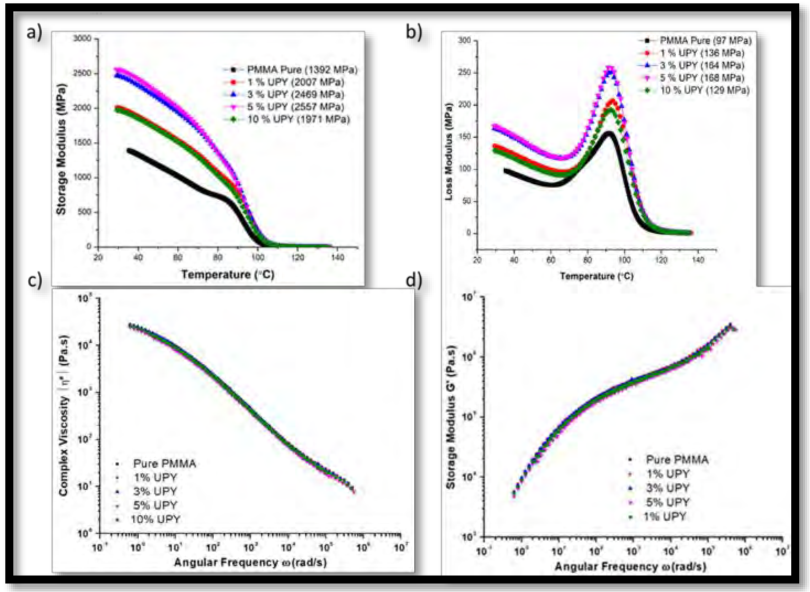
Tailoring Interfacial Interactions via Polymer-Grafted Nanoparticles Improves Performance of Parts Created by 3D Printing

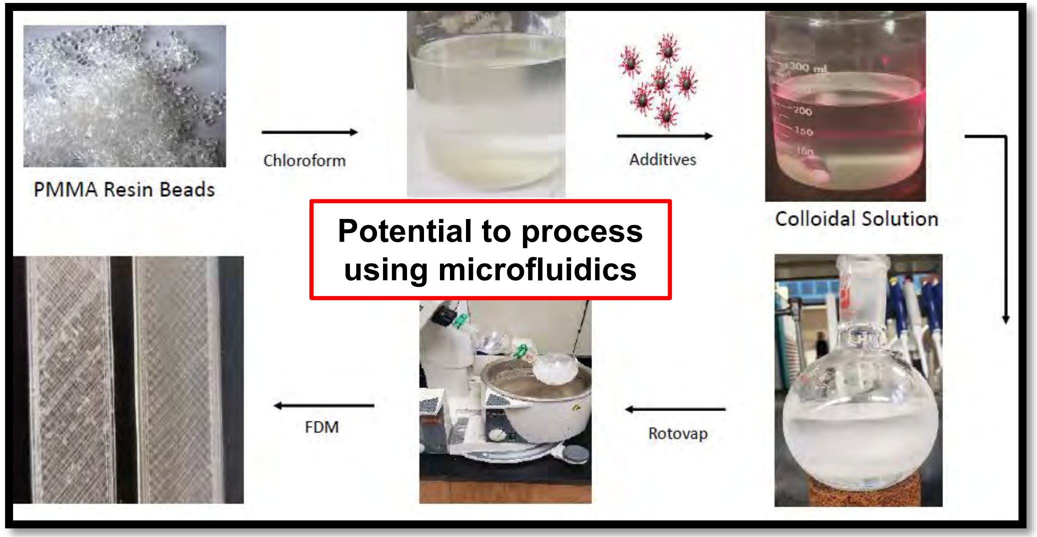
Dayton P. Street, Adeline Huizhen Mah, William K. Ledford, Steven Patterson, James A. Bergman, Bradley S. Lokitz, Deanna L. Pickel, Jamie M. Messman, Gila E. Stein, and S. Michael Kilbey II*

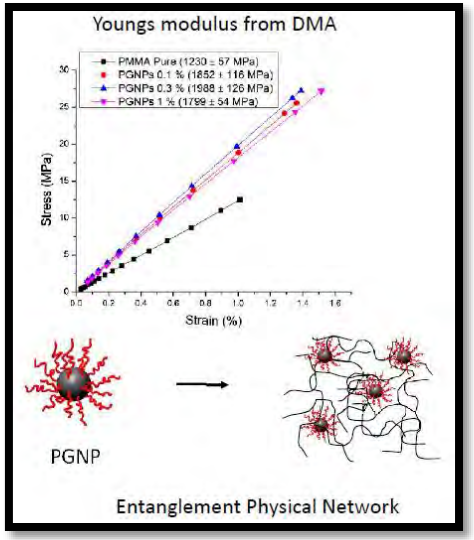
Cite this: *ACS Appl. Polym. Mater.* 2020, 2, 3, 1312–1324
Publication Date: February 10, 2020
https://doi.org/10.1021/acsapm.9b01195









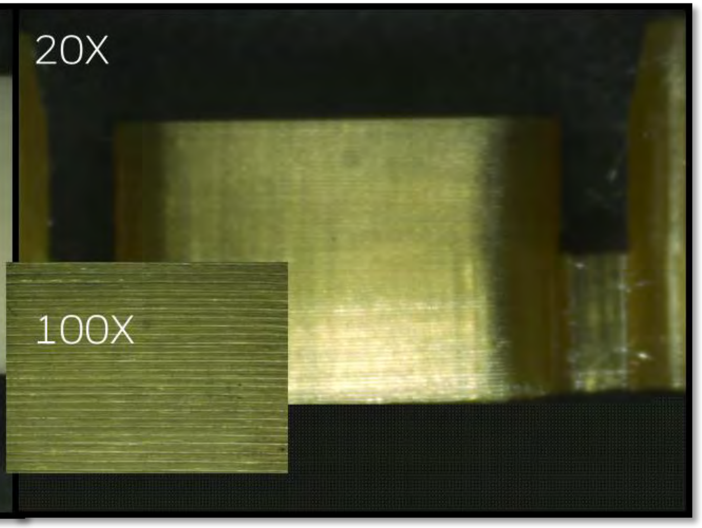


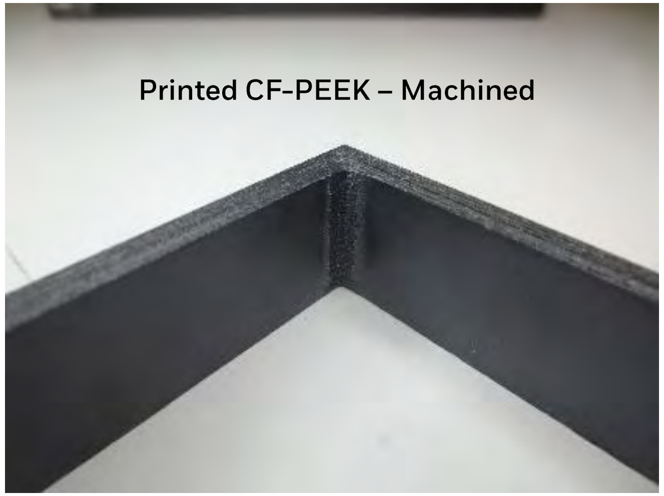
Small incorporation of H-bonding group (UPY) onto nanoparticles results in mechanically stronger parts while not affecting rheology/processing.

3D PRINTING OF PEEK/ULTEM USING AON-M2 PRINTER

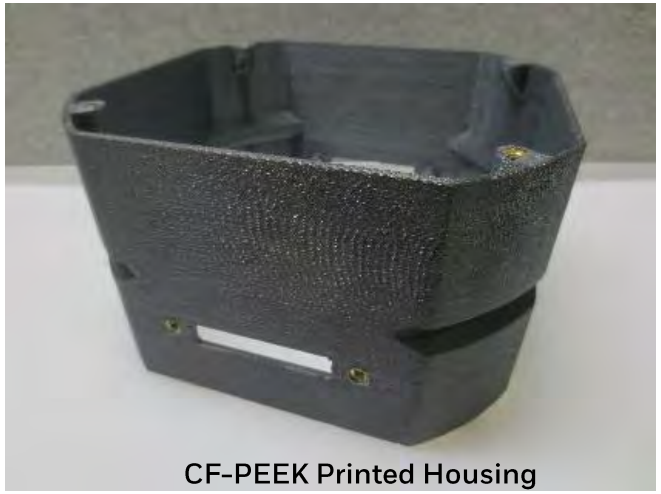
PEEK- 0.2 mm layer heights

Ultem 1010- 0.1 mm layer heights





Printed CF-PEEK – Machined

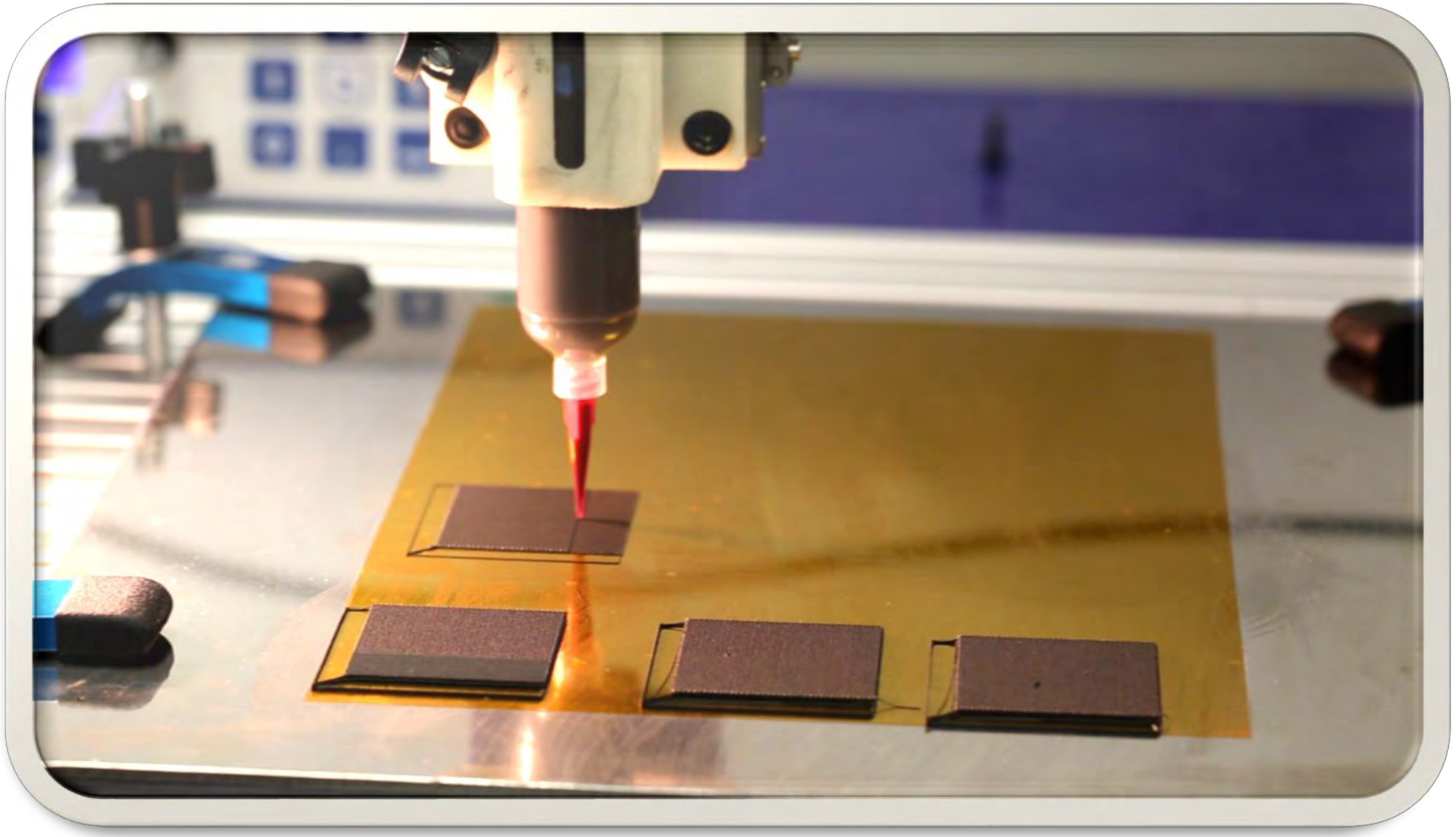


CF-PEEK Printed Housing

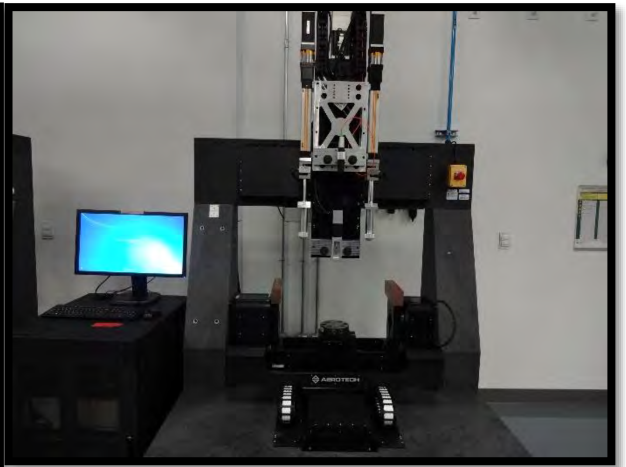
- System has successfully printed – PEEK and ULTEM 1010 amongst a variety of other engineering plastics (ABS, ASA, PC, etc.)
- PEEK and carbon fiber-filled PEEK parameter development is ongoing

DIRECT INK WRITE (DIW)

Technology Overview



DIW EQUIPMENT/CAPABILITIES

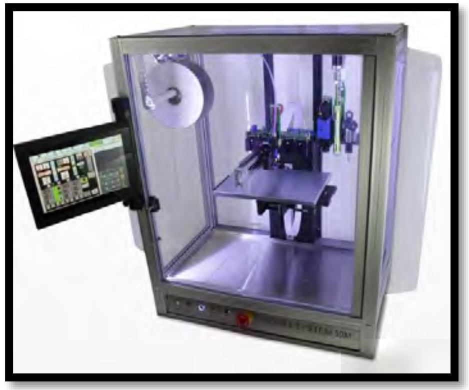


Aerotech 5-Axis Machines, KCNSC

Aerotech 3-Axis Production Machine, 4x Print Head/Substrate, KCNSC

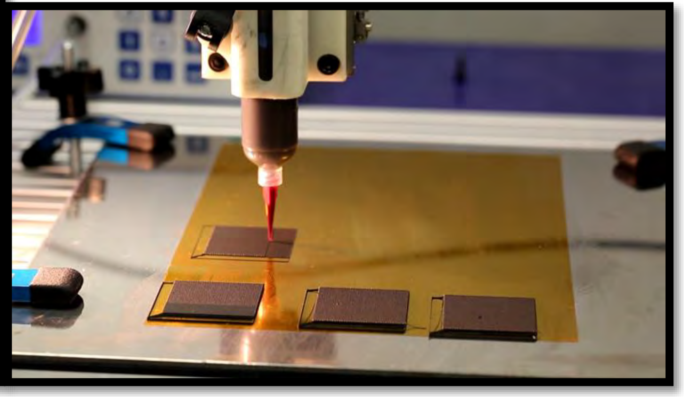
https://www.viscotec-america.com/industry-applications/3d-printing

Viscotec Print Heads, KCNSC



http://www.hyrel3d.com/portfolio/system-30m/

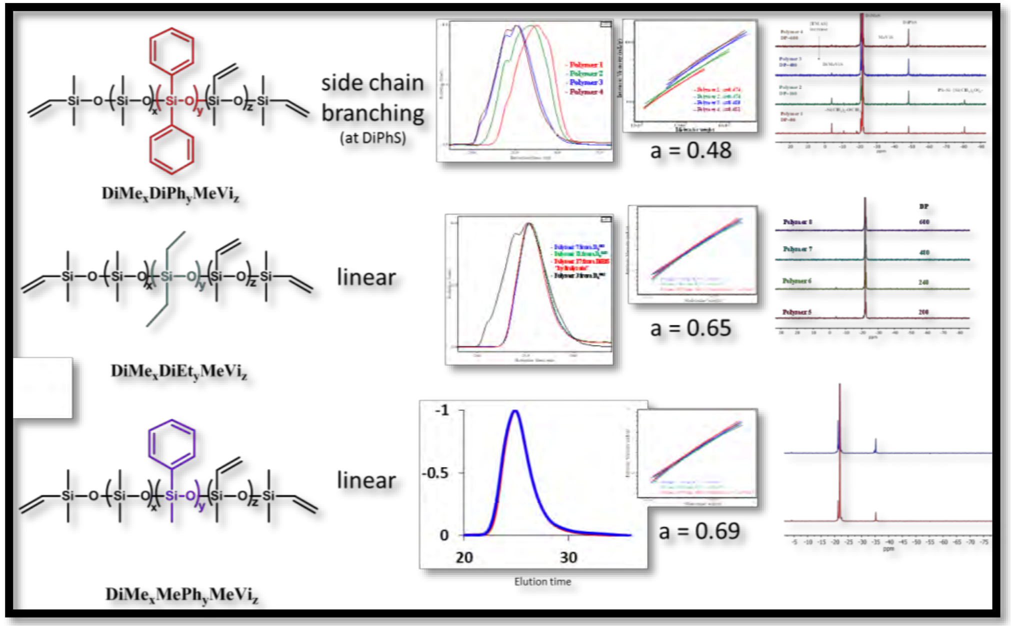
Hyrel System 30M, KCNSC

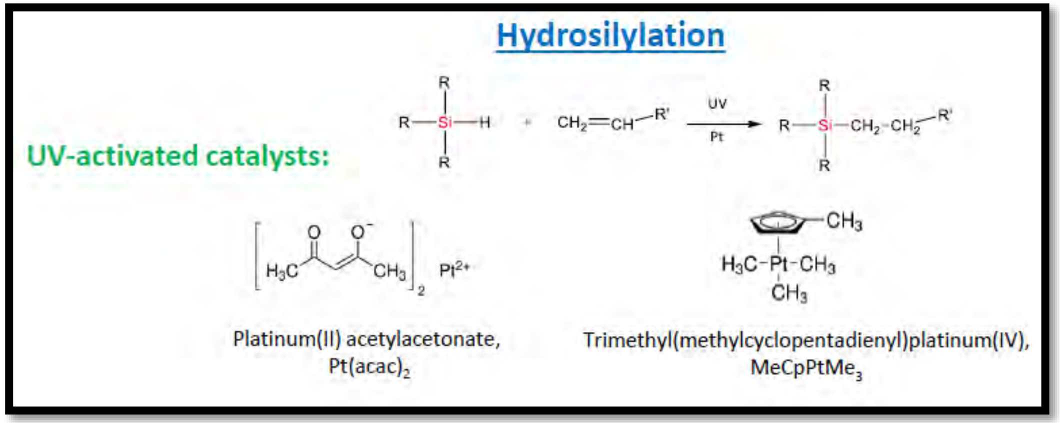


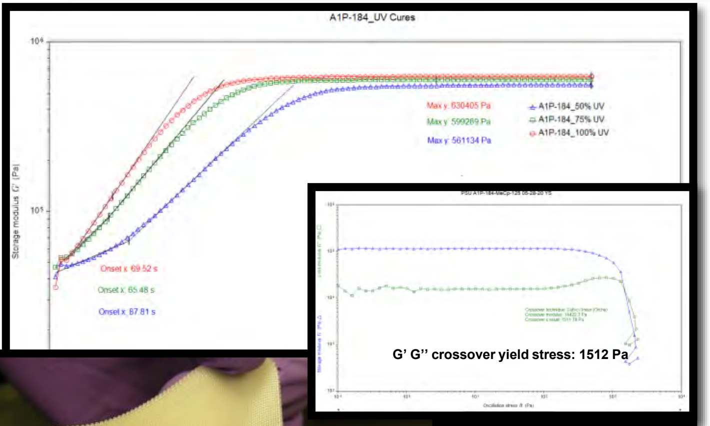
ShopBot 3-Axis Benchtop, KCNSC

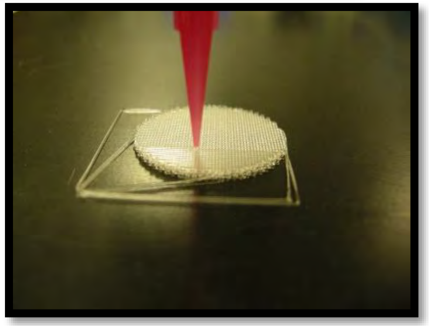
Silicone DIW Resins: Polymer Structure Influences Processing & Aging

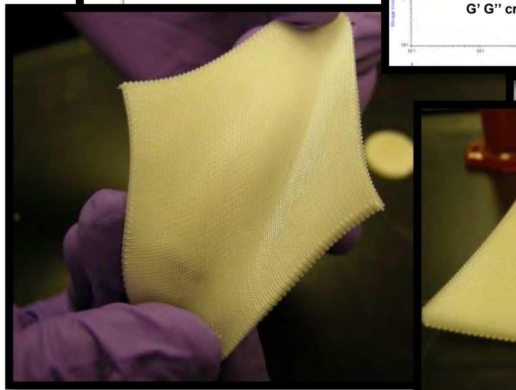
Comonomer ↔ Polymerization ↔ Properties

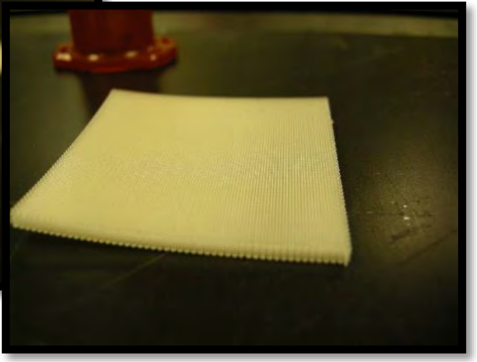












- DiPhS incorporation is more difficult to control polymerization
- DiPhS leads to branched polymer structure and is more difficult to compound (high MW)
- DiPhS very electrophilic Si center is more prone to side reactions (chemically binds to silica fillers)

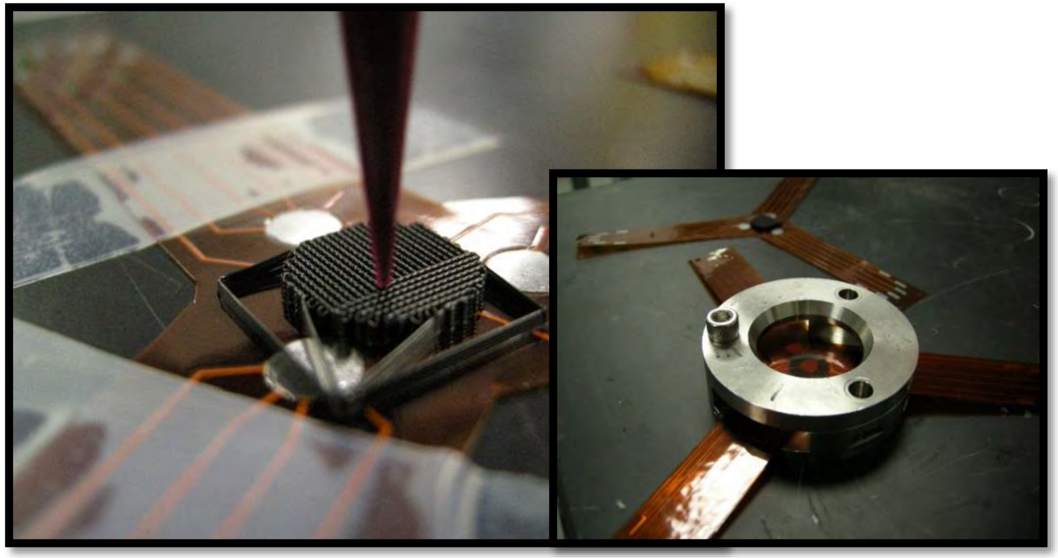
Macromolecules, **2017**, *50*, 3532; **2018**, *51*, 895.

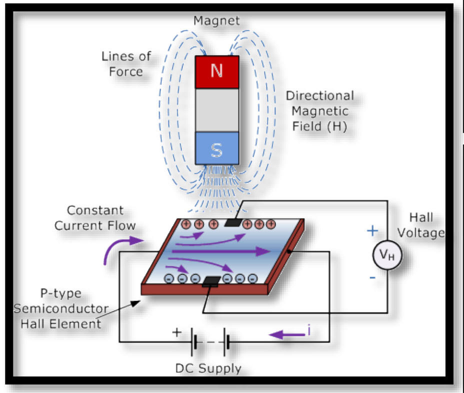
“All-in-one” silicone ink (paste) for DIW:

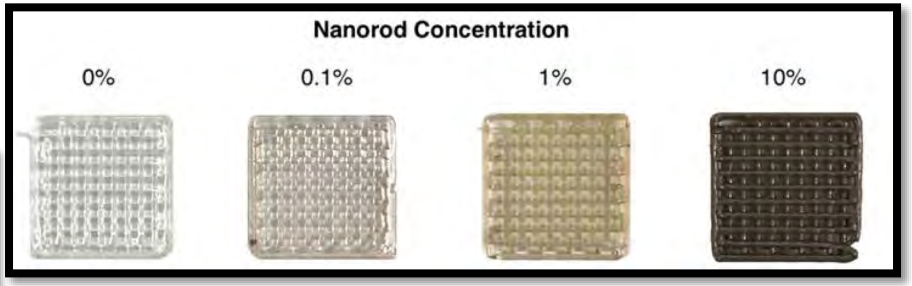
- **No low T crystallinity**
- **Low outgassing**
- **Tunable stiffness**
- **Improved aging**
- **UV curable**

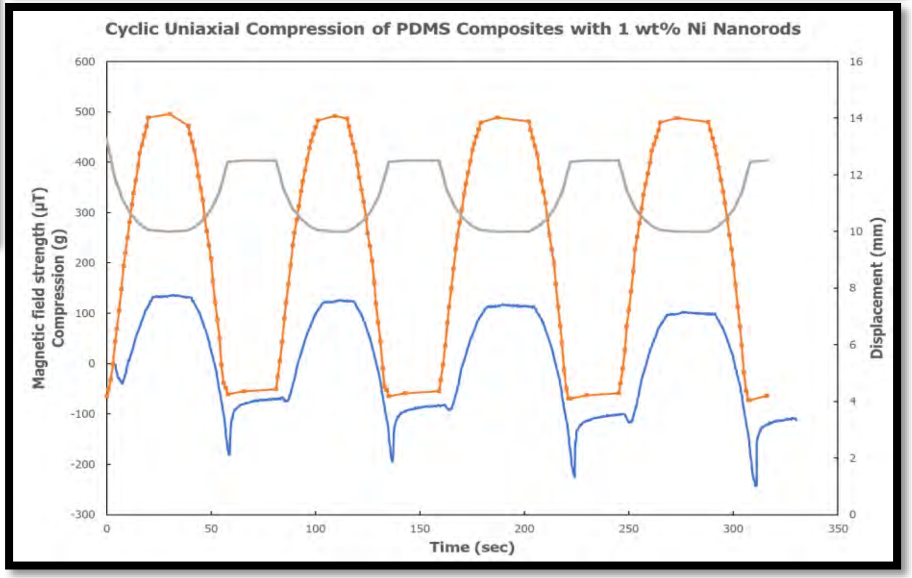
Thanks to Pittsburg State University

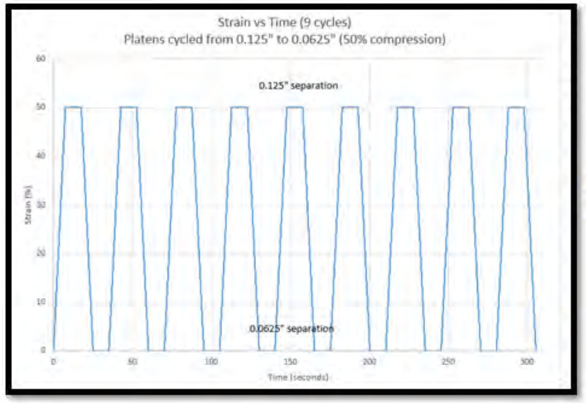
“SMART” DIW SILICONE PADS

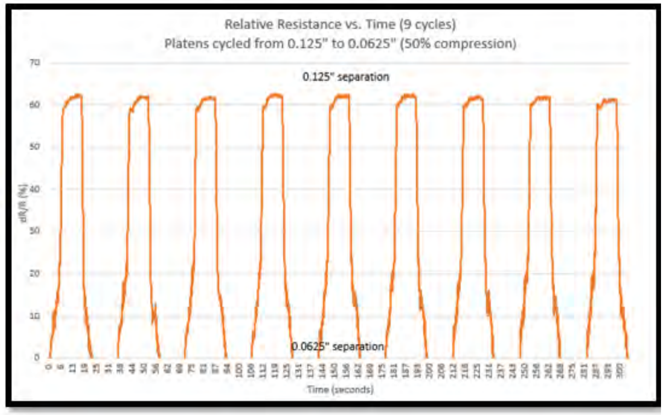












Carbon-based fillers can impart piezoresistive functionality to DIW silicones with little impact on rheology

Ferromagnetic fillers provide the ability to detect changes in magnetic field when a printed part is under stress or strain “wirelessly” via Hall Effect Sensor (triple-axis magnetometer)

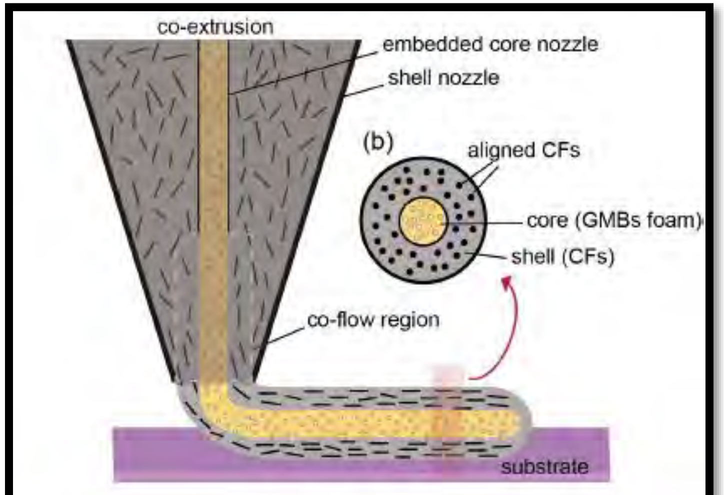
Thanks to the University of Kansas

Thanks to the University of Oklahoma

Thermoset Foams via DIW

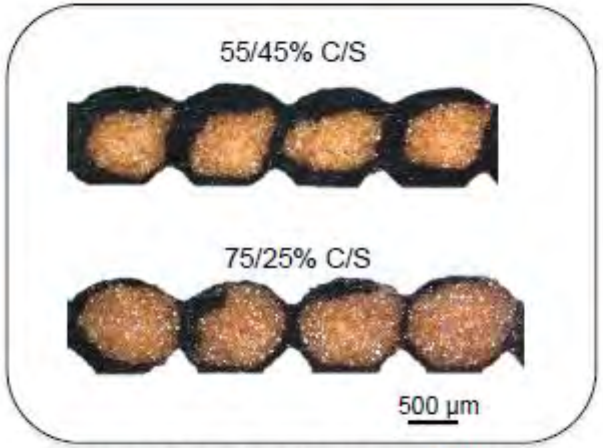
Desire to find replacement materials for rigid syntactic materials

Stiffness, load-bearing capability, and tight dimensional tolerance

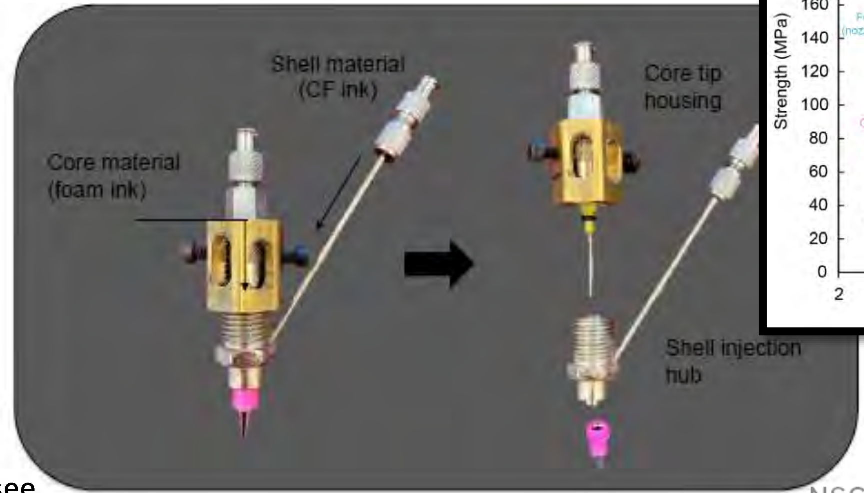


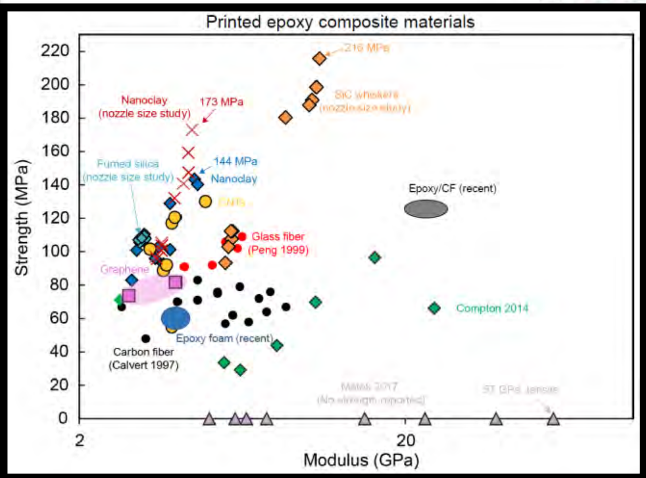
DW schematic of epoxy foam core-CF shell printing. Notice nozzle design incorporates co-flow region and CFs are aligned due to shear nature of DW extrusion.

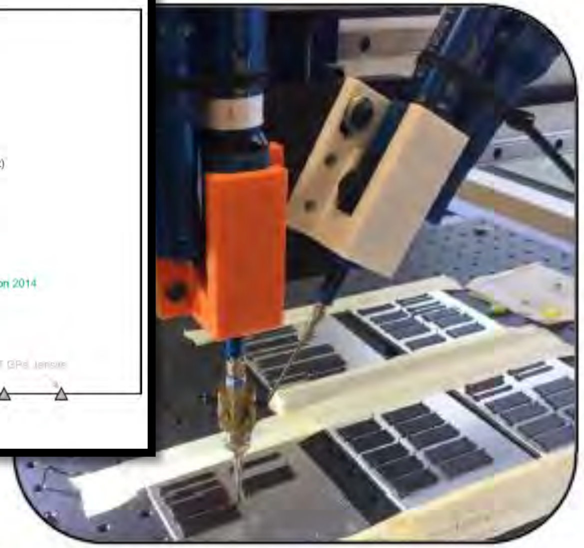
Porcupine quill



Cross-sections showing core volume control







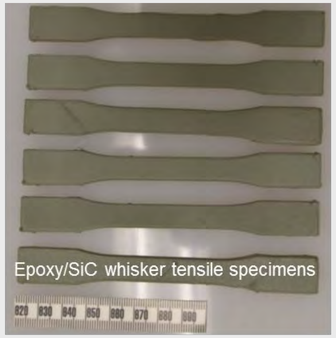
Printing of single layer flexural bars with C-S nozzle

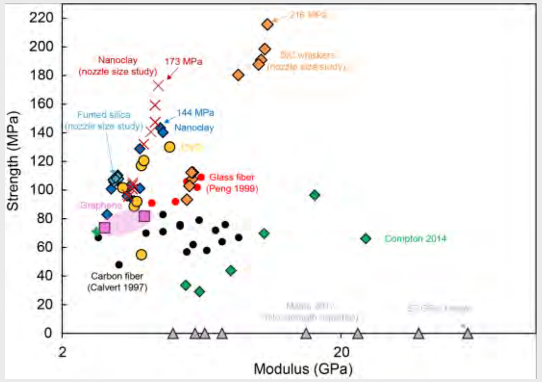
Thanks to the University of Tennessee

THERMOSET AM: FORMULATION, ENHANCED PROPERTIES, & PRECERAMIC POLYMER RESINS

Materials for Extreme Environments - Targeting Metal Properties with Polymers

Formulation

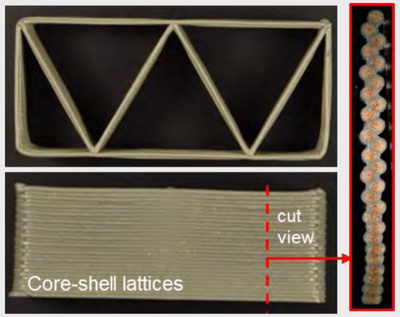


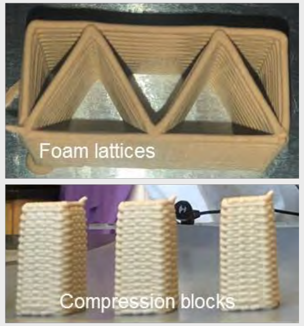


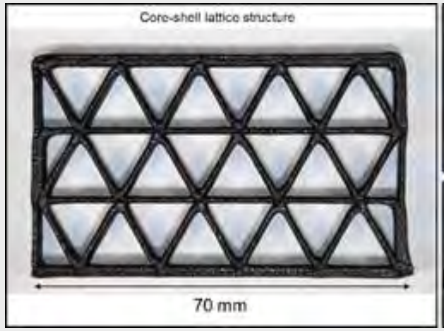
Observations

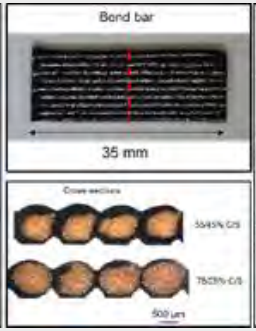
- New formulations and process studies have led to significant improvements in strength and stiffness of printed epoxy composites
- Print resolution, print speed, filler morphology, and mechanical anisotropy in printed parts are tightly coupled.
- Isotropic filler appears to result in size-independent, rate-independent properties with >100 MPa strength
- The transverse strength of SiC whisker-containing formulations matches that of the isotropic formulation.

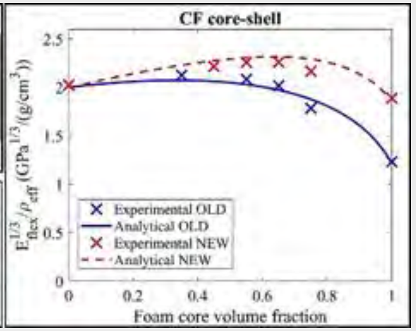
APO-BMI Replacement



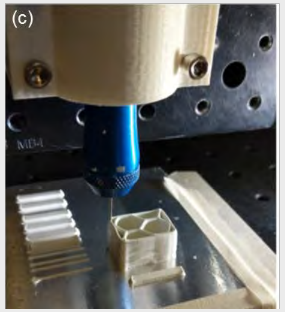


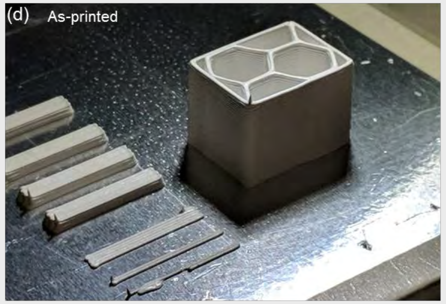


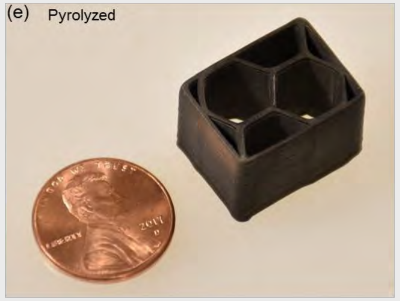




Preceramics







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