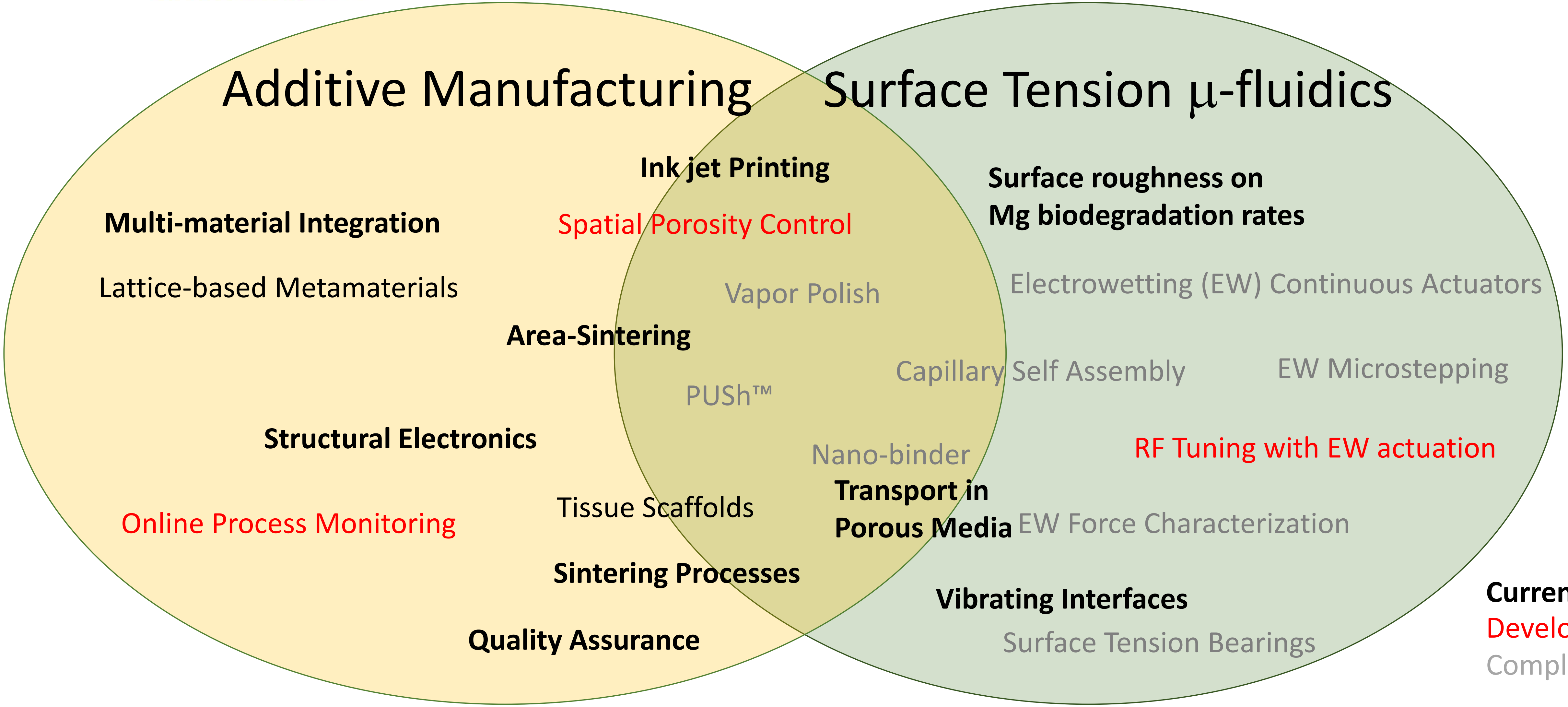
Additive Manufacturing of Continuous-fiber Composites by Selective Resin Infusion

Nathan B. Crane, Andy George, Jason Weaver
nbcrane@byu.edu

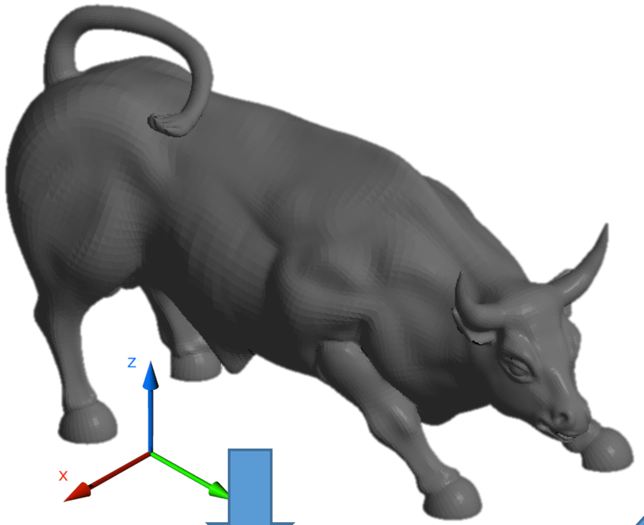
BYU Mechanical Engineering
IRA A. FULTON COLLEGE OF ENGINEERING

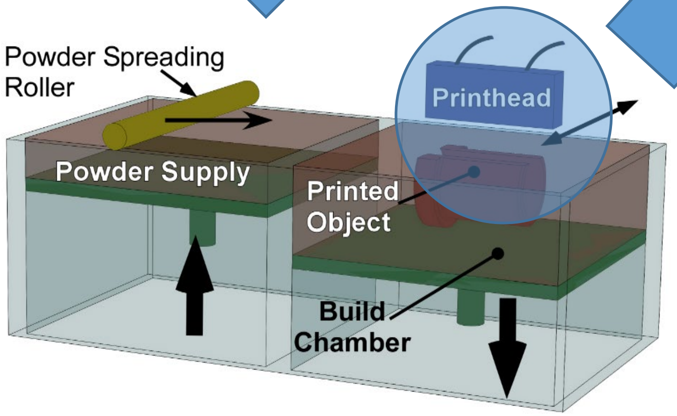
CREATE Research Lab Lab Activities



Current
Developing
Completed

Binder Jetting Additive Manufacturing





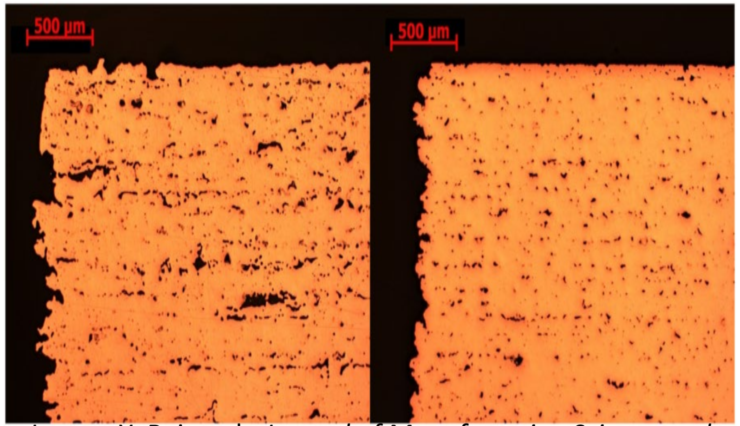
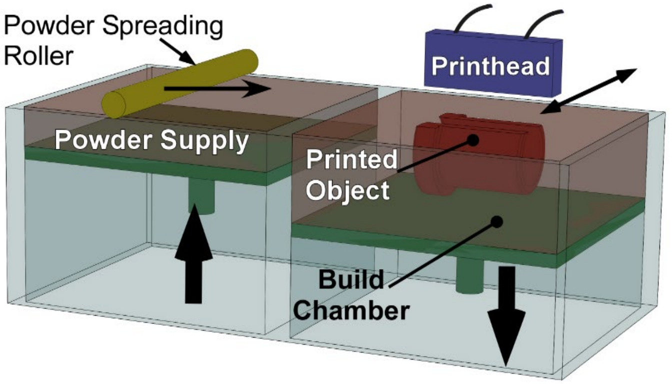


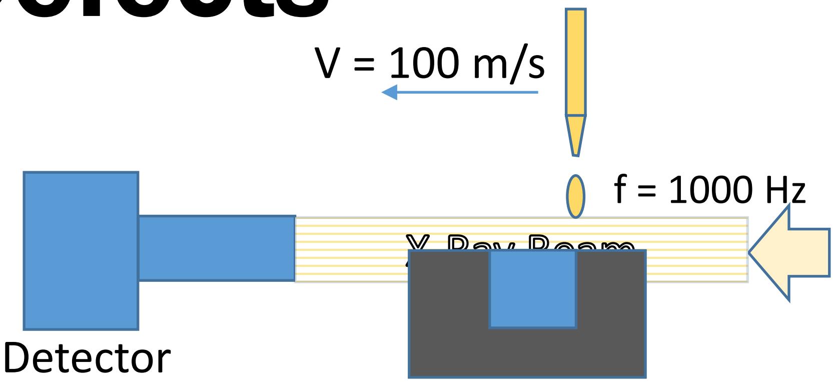
Image: Y. Bai et al., *Journal of Manufacturing Science and Engineering*, 2017.

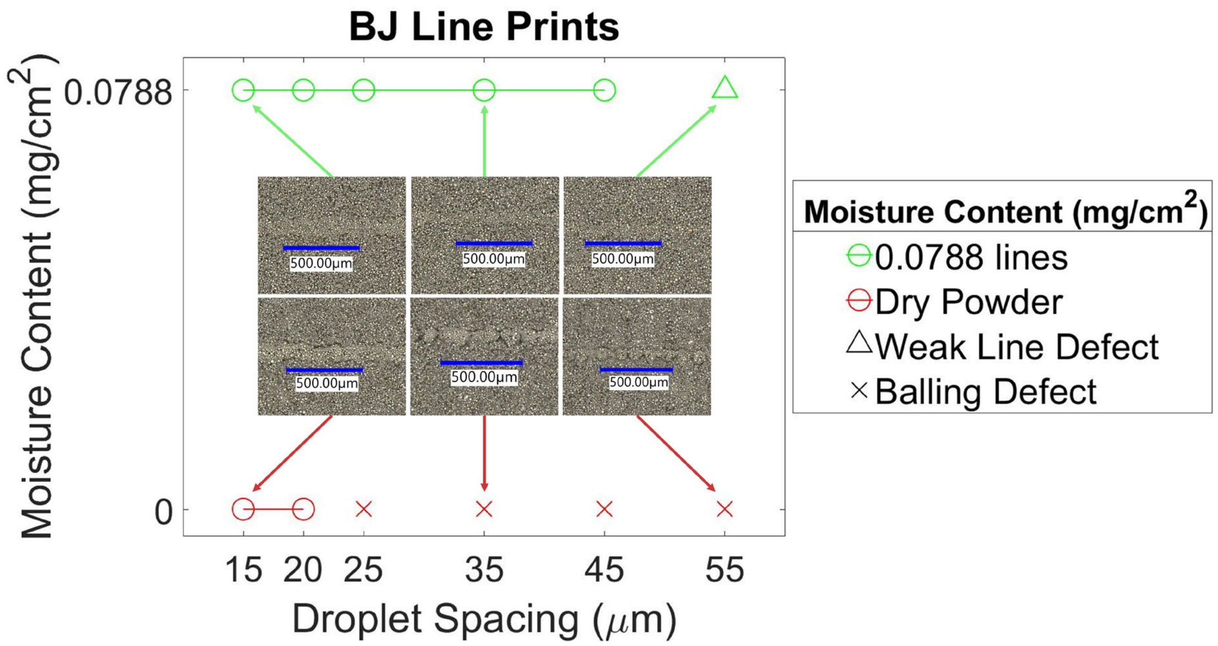
Printing parameters impact rest of the process.

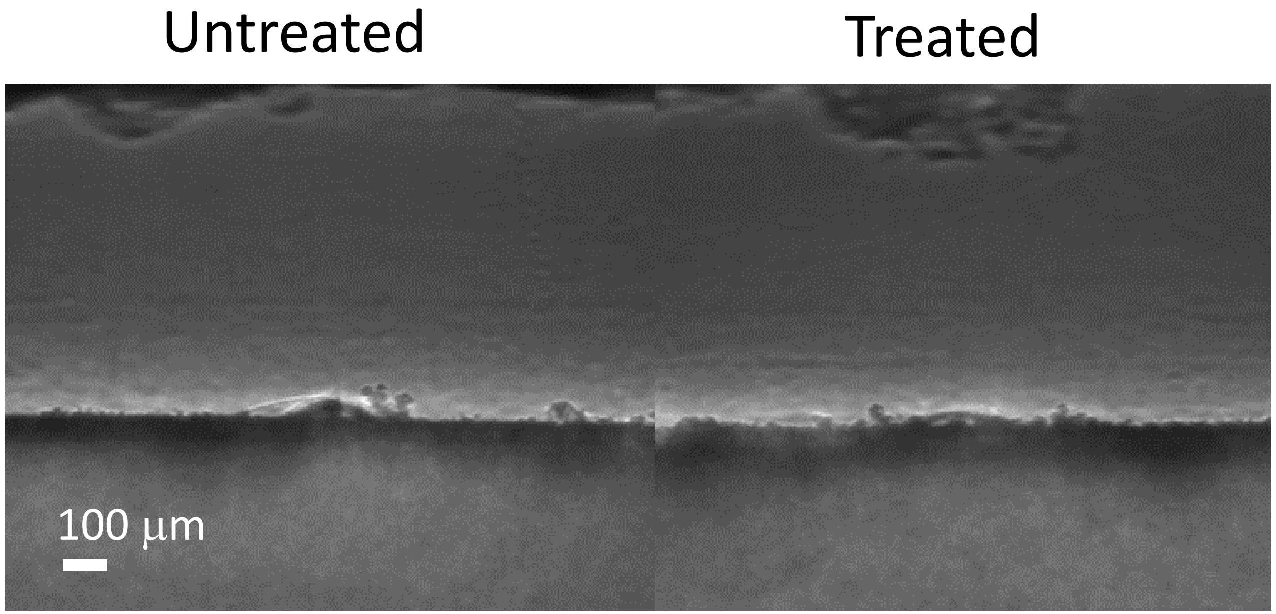
Binder Jetting – Eliminating Defects



High Speed X-Ray Imaging of the Binder Printing Process

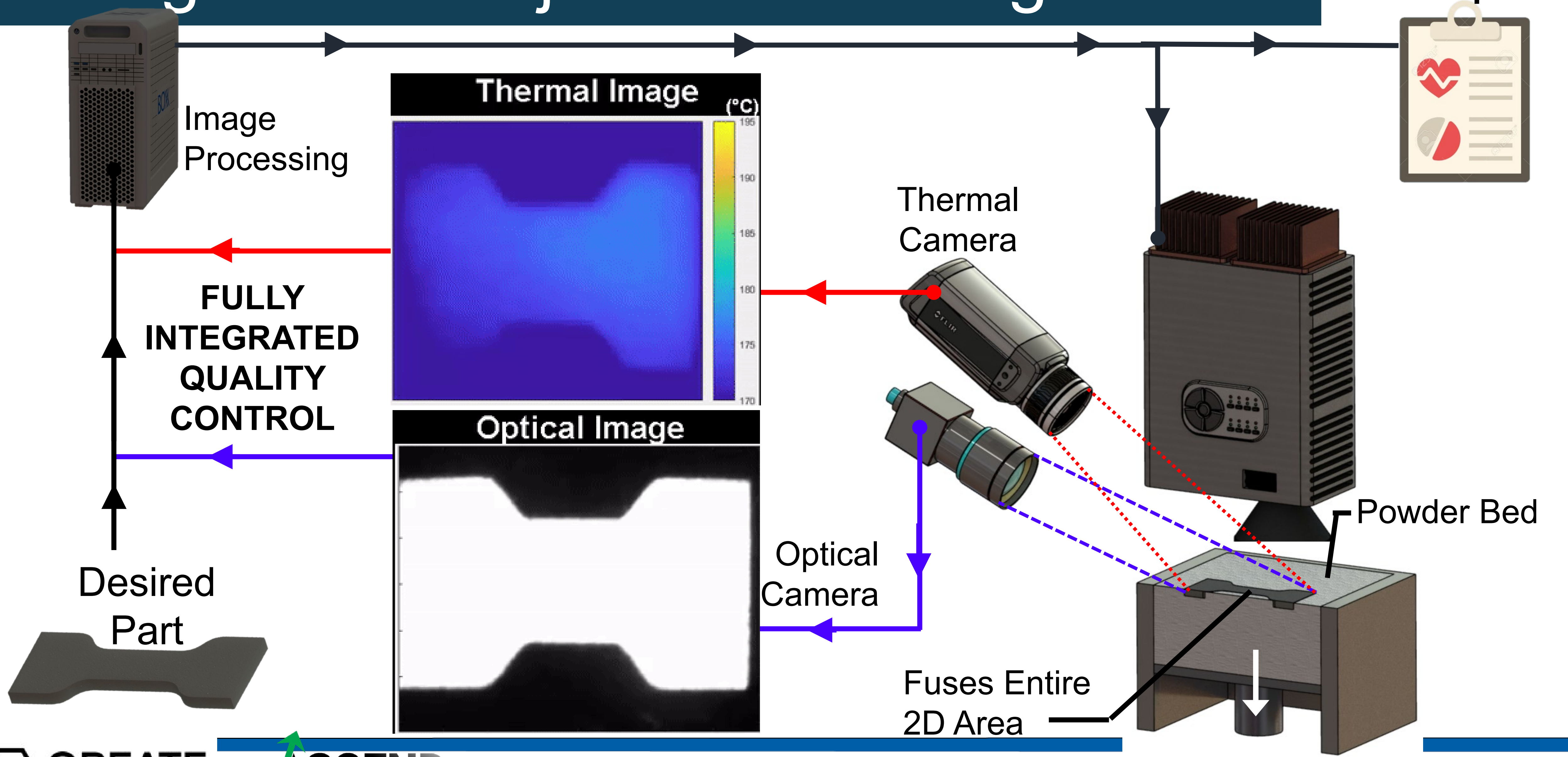




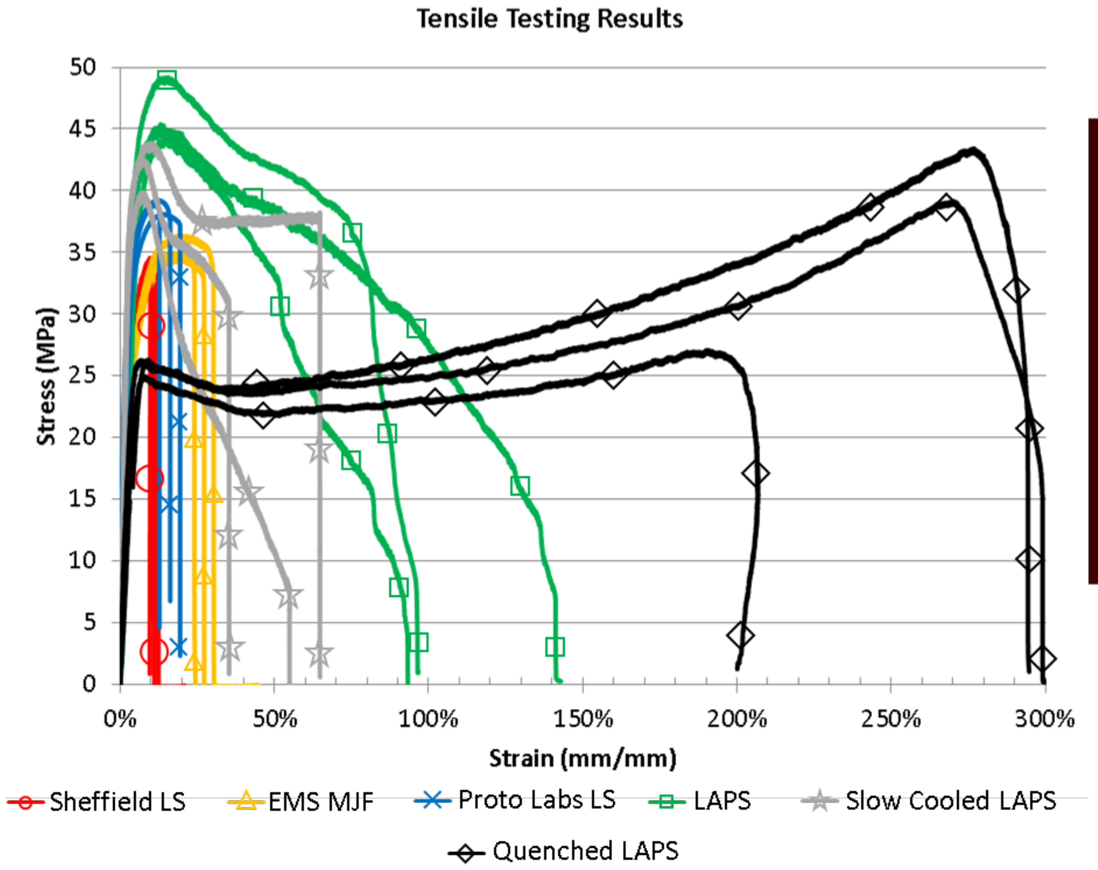


CREATE Research Lab Argonne NATIONAL LABORATORY Advanced Photon Source BYU Mechanical Engineering

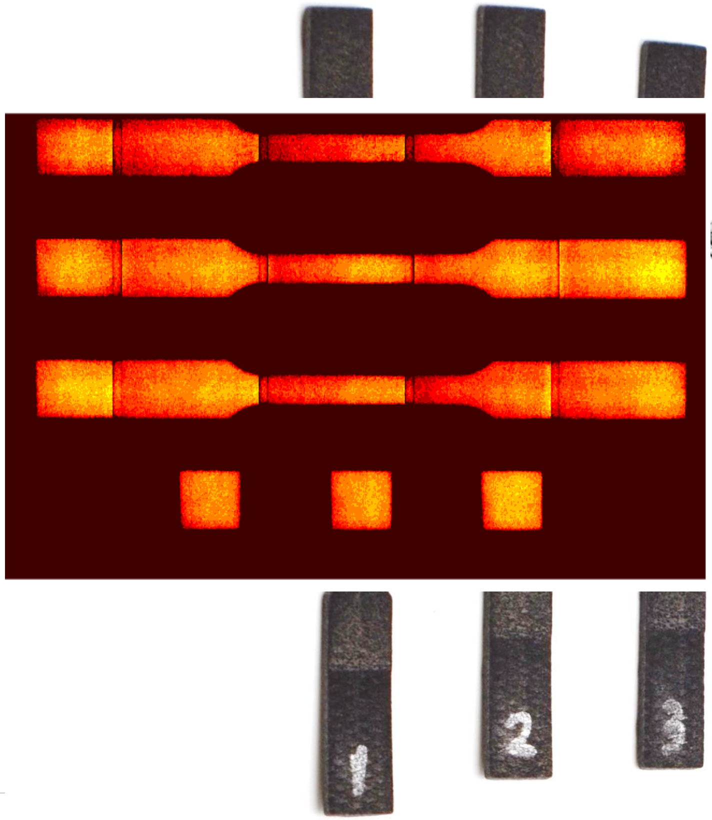
Large Area Projection Sintering

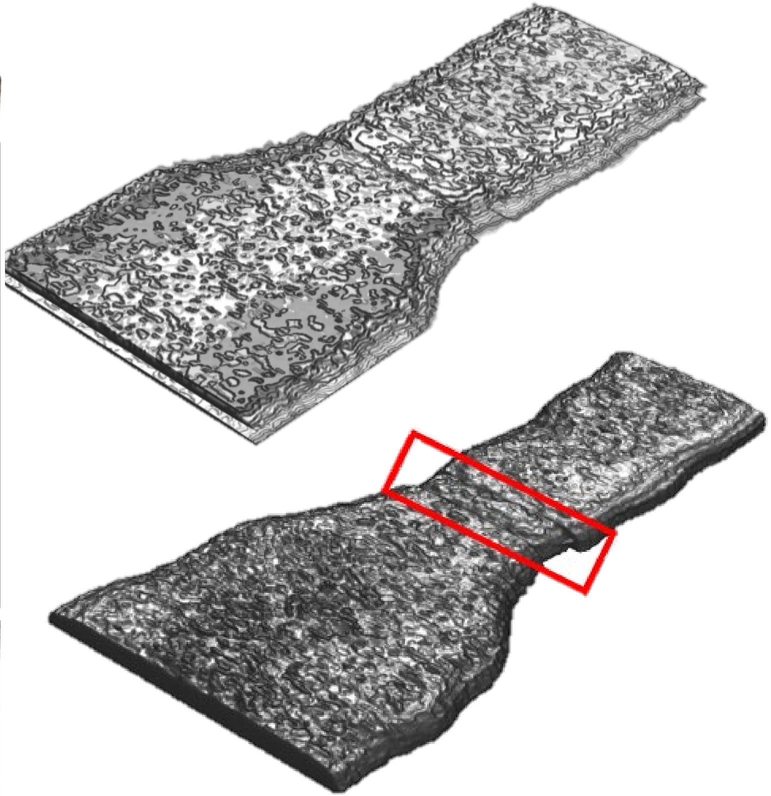


LAPS – Polymer Sintering

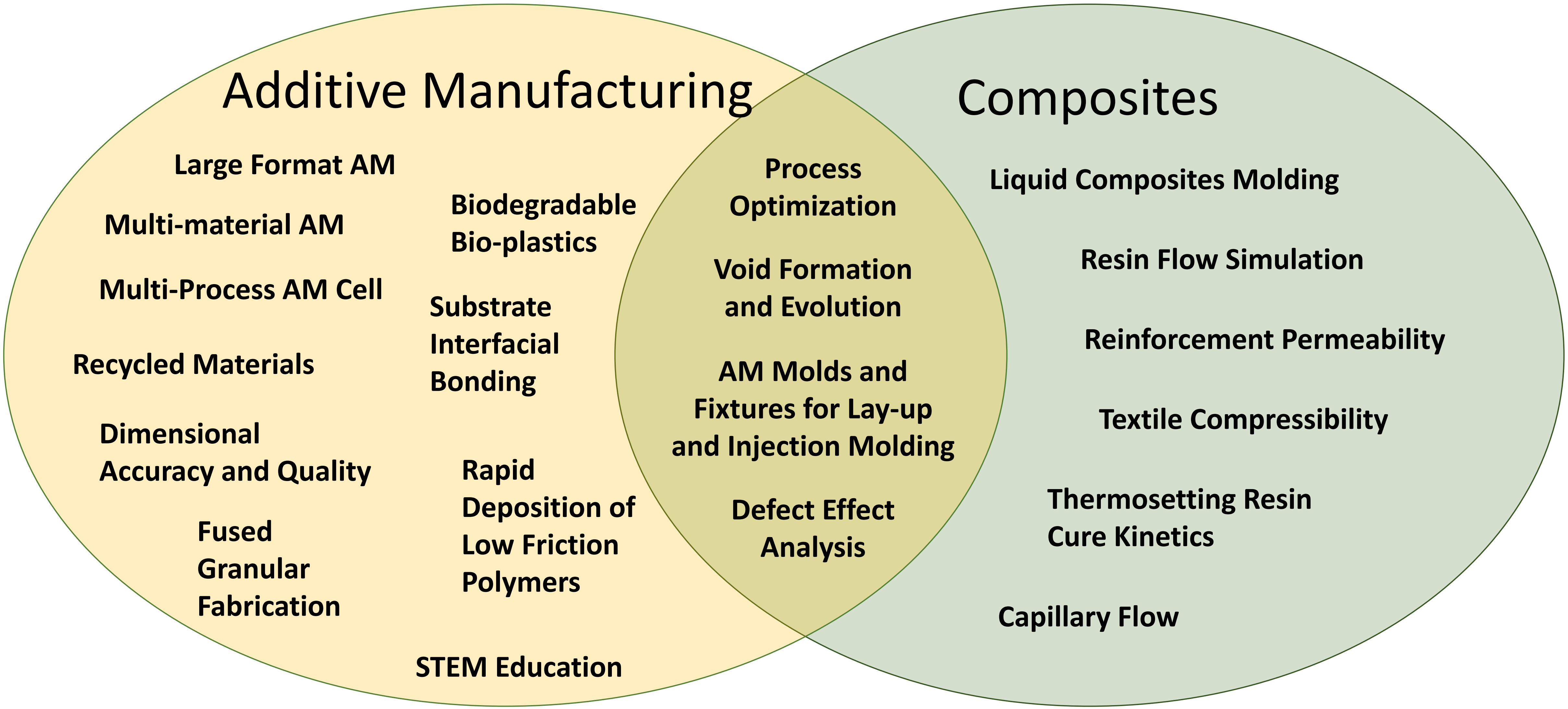


Brittle Failure

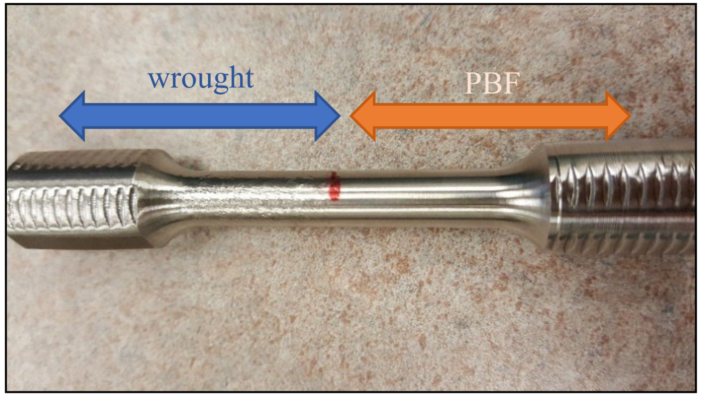


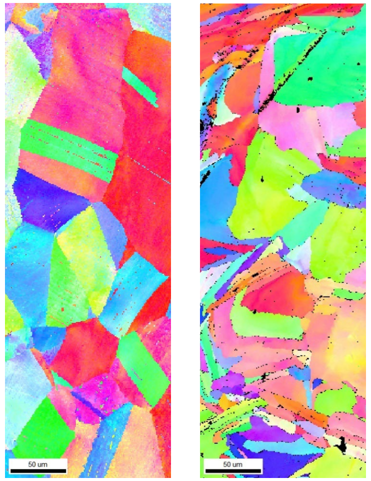


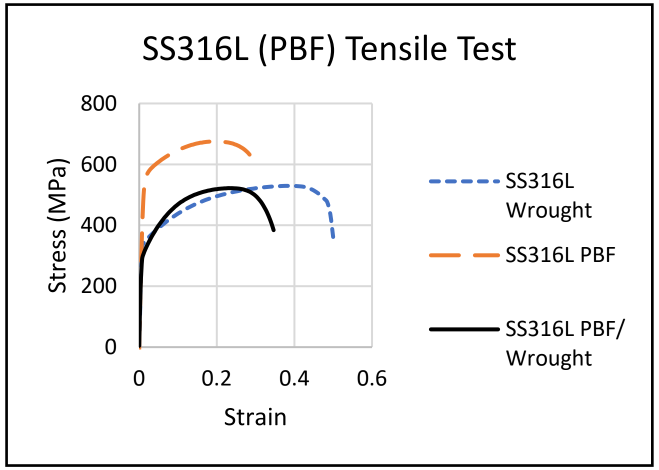
Manufacturing Engineering Activities

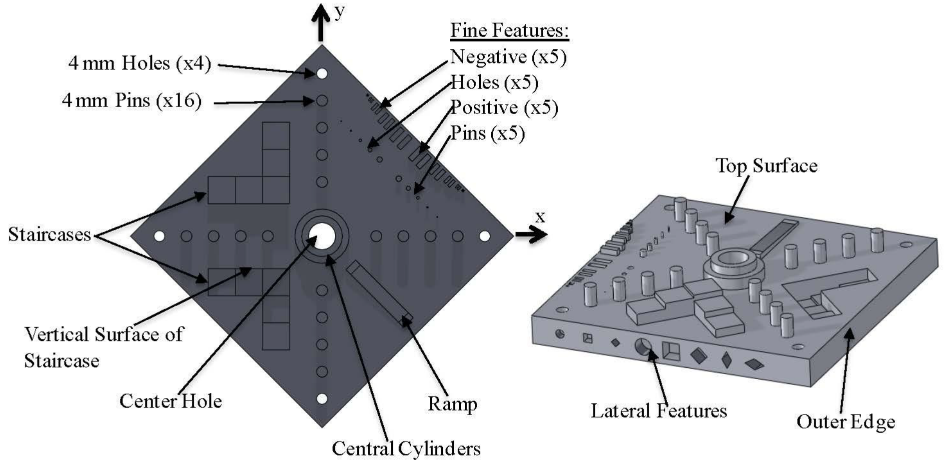


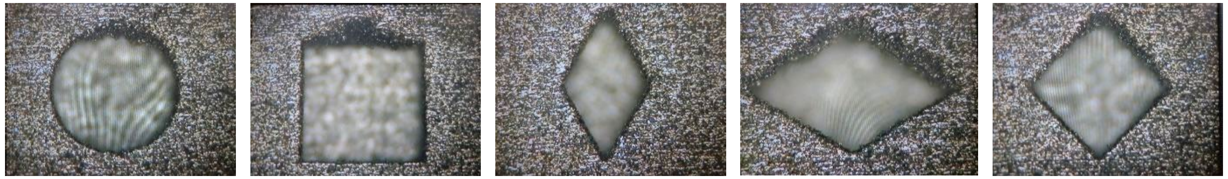
Material and Dimensional Analysis











Selective Resin Infusion (SRI)

Vacuum Infusion Composite Manufacturing

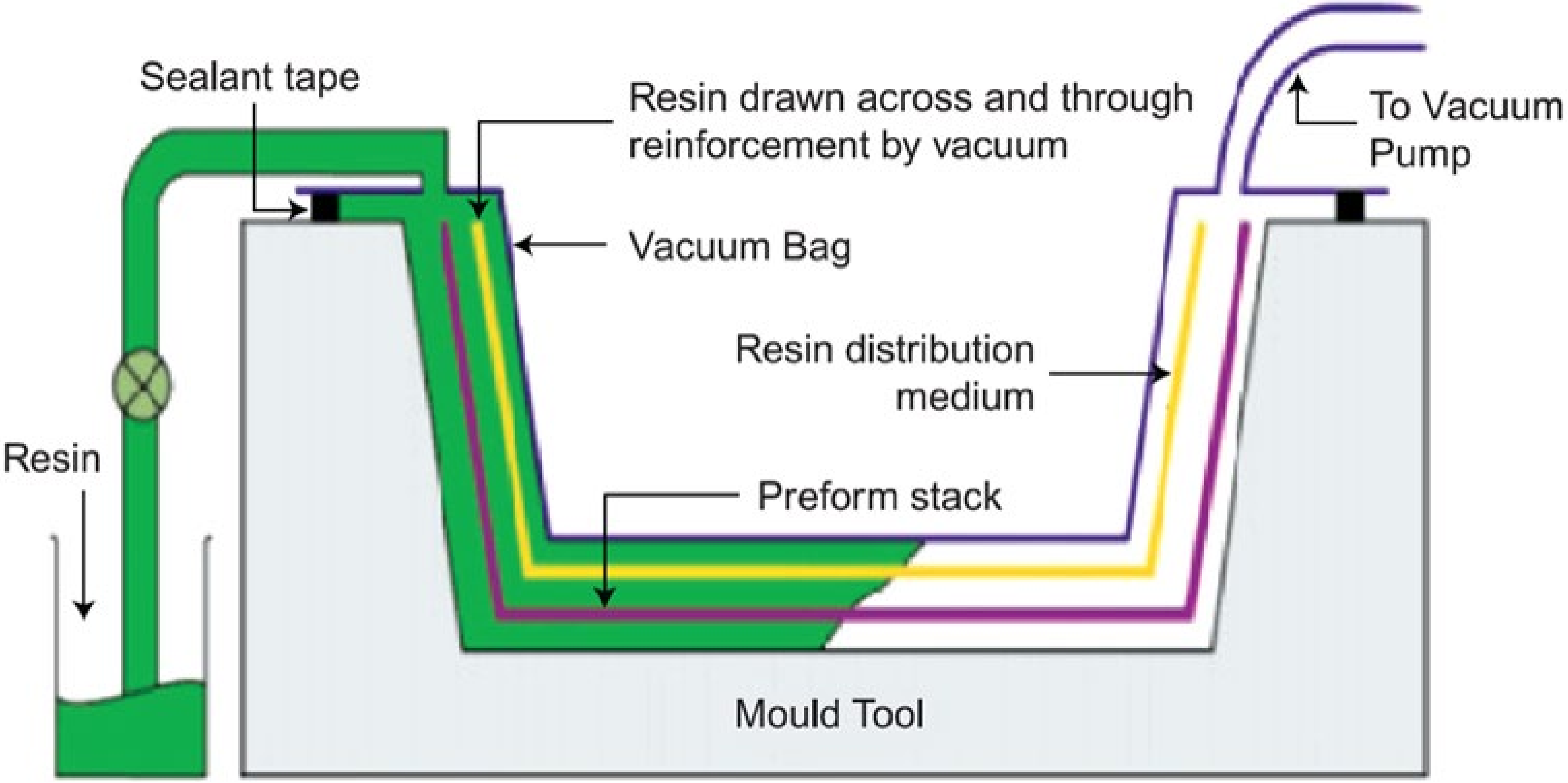
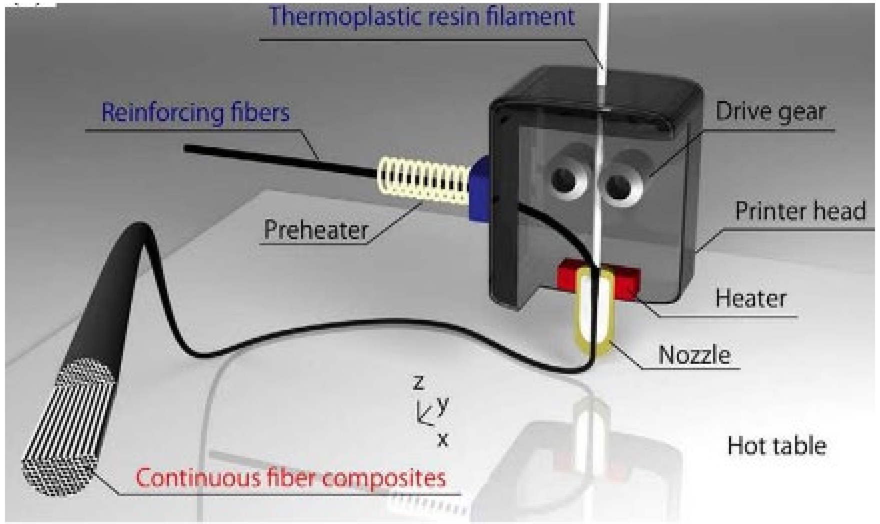
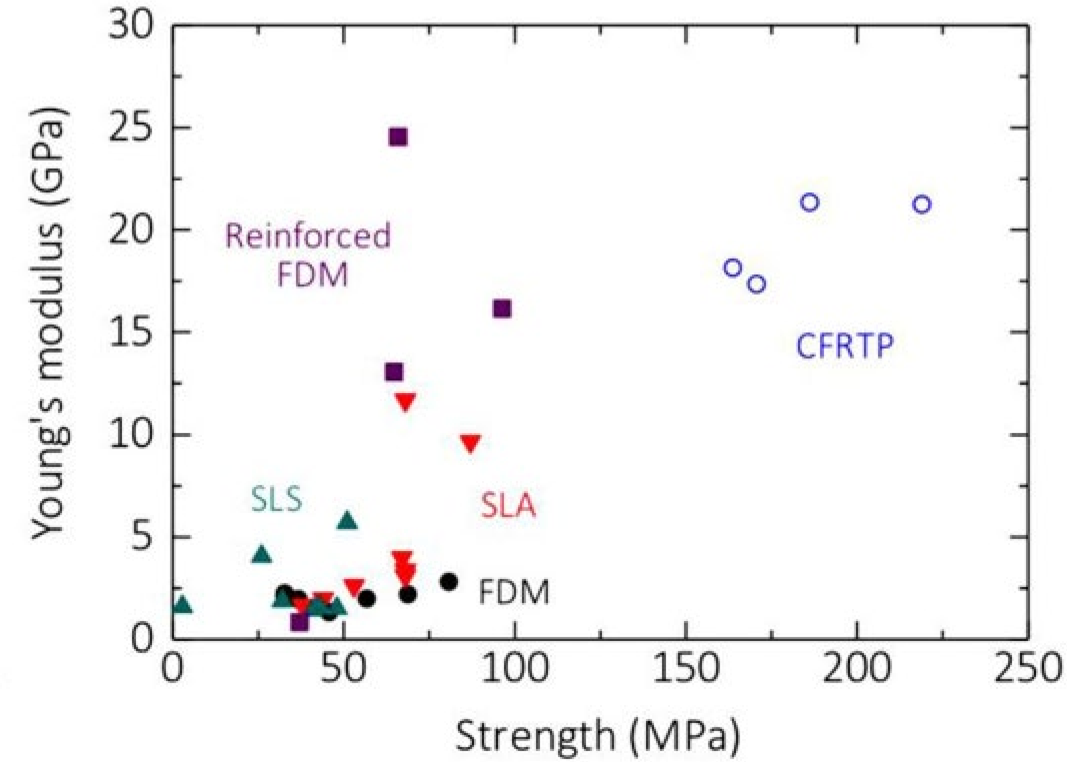


Image: https://www.nal.res.in/en/techniques/vacuum-enhanced-resin-infusion-technology

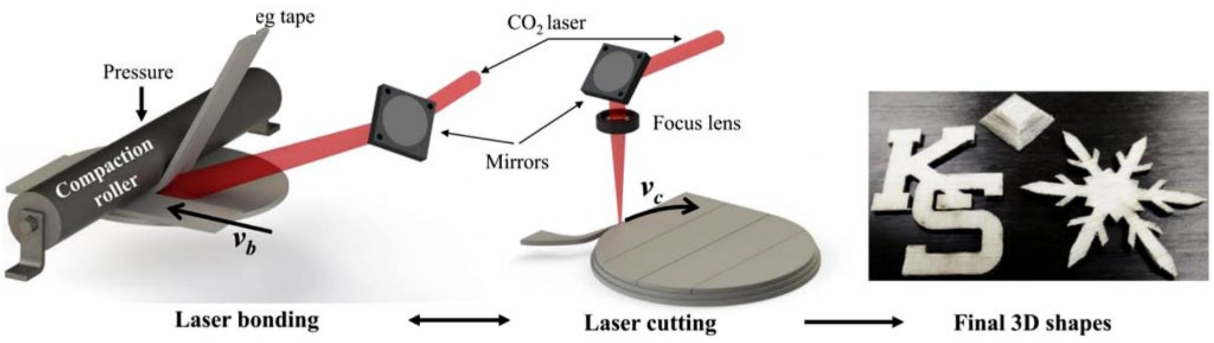
AM of Composites

Extrusion (FDM) with Continuous Fibers:





Laminated Object Manufacturing with Pre-Preg:



Standard Composite Manufacturing Properties

Fiber	Young's Modulus (GPa)	Ultimate Strength (MPa)
Carbon Fiber/Epoxy	70-175	600-1500
E Glass/Epoxy	25-40	440-1000
Kevlar/Epoxy	30-75	480-1300

CBAM Process (Impossible Objects)

Step 1

Feed fiber sheet into inkjet printer.

Step 2

Load CAD slices into printer and print layer shape of object on fiber sheet.

Step 3

Deposit polymer powder onto printed sheet which sticks to where the sheet is wet from print fluid.

Step 4

Remove dry powder; only powder stuck to the print fluid remains.

Step 5

Stack sheets in order, heat to melting T^{o} of polymer, and compress stack to final part height.

Step 6

Remove un-bonded portions of sheet fibers to net final part.

Show images of our parts

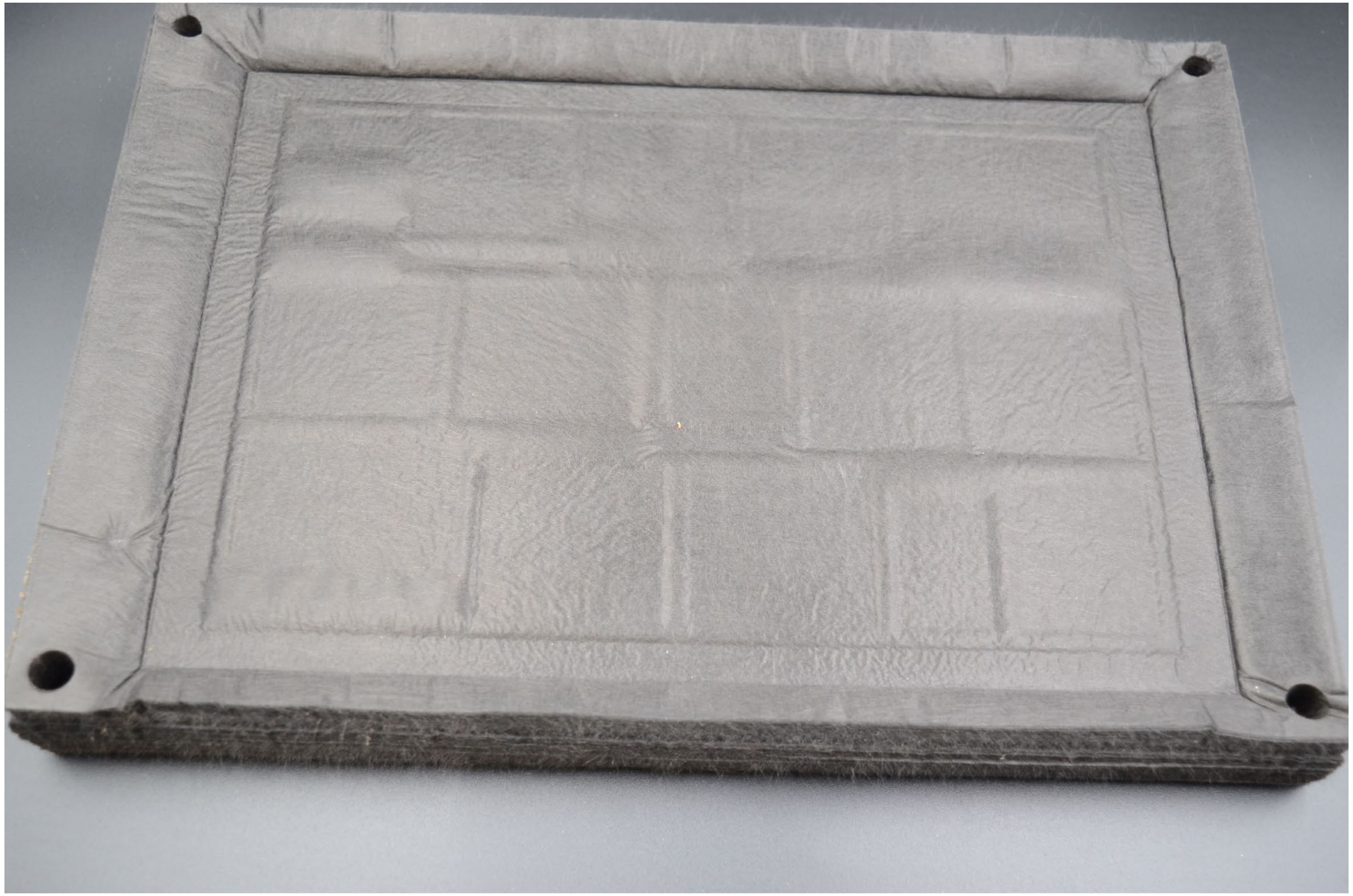
Challenges:

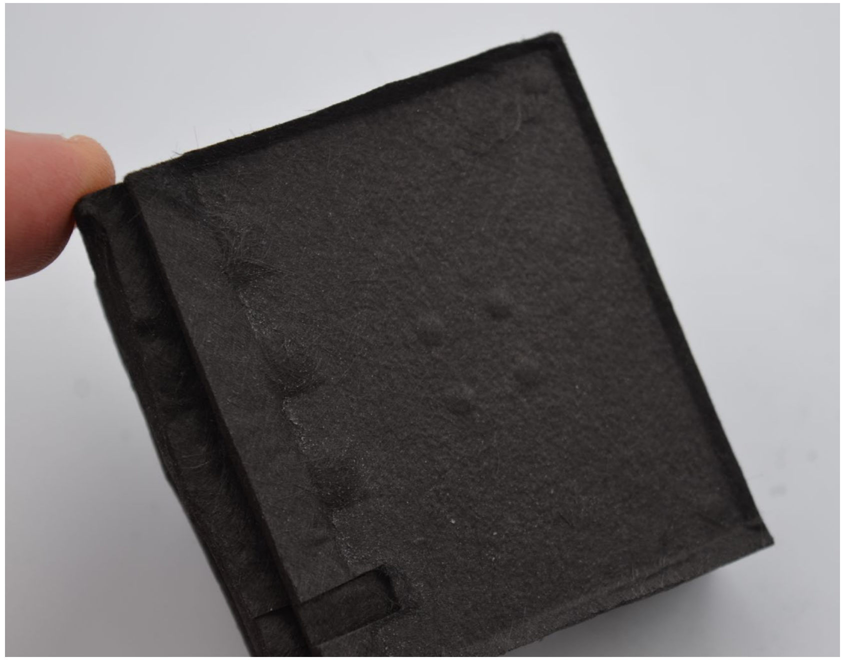
- No Support Material
- Thermoplastic materials
- Single Plane of nonwoven fibers

Standard of comparison is FDM rather than high performance composites.

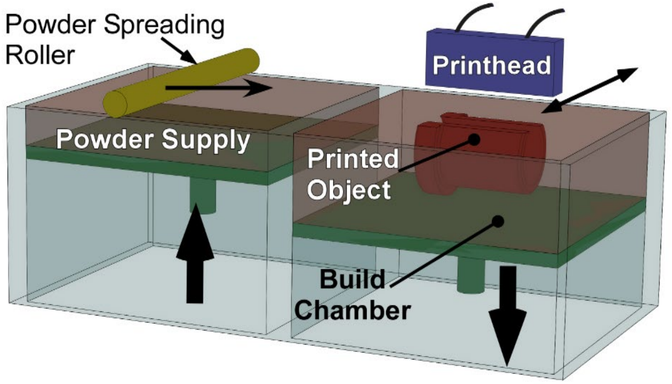
https://www.3dprintingmedia.network/impossible-objects-unveils-next-gen-3d-printer-for-composites/

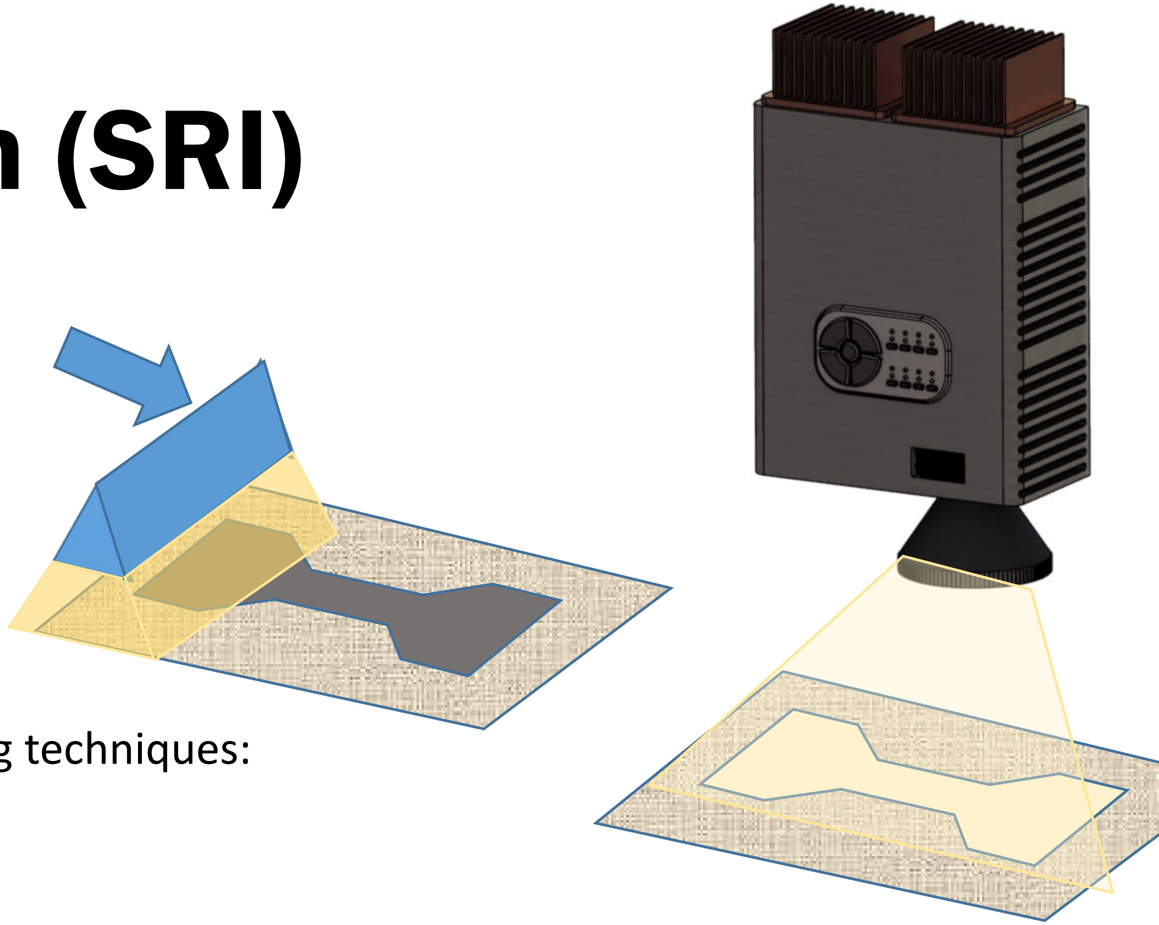
CBAM-Fabricated Hinges



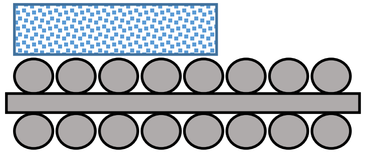


Selective Resin Infusion (SRI)





Pattern
Matrix Powder

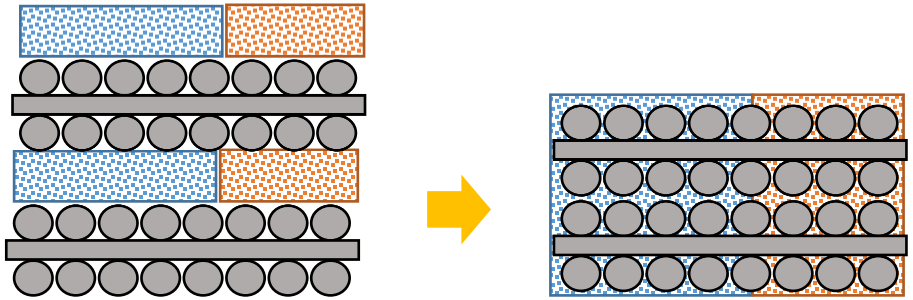


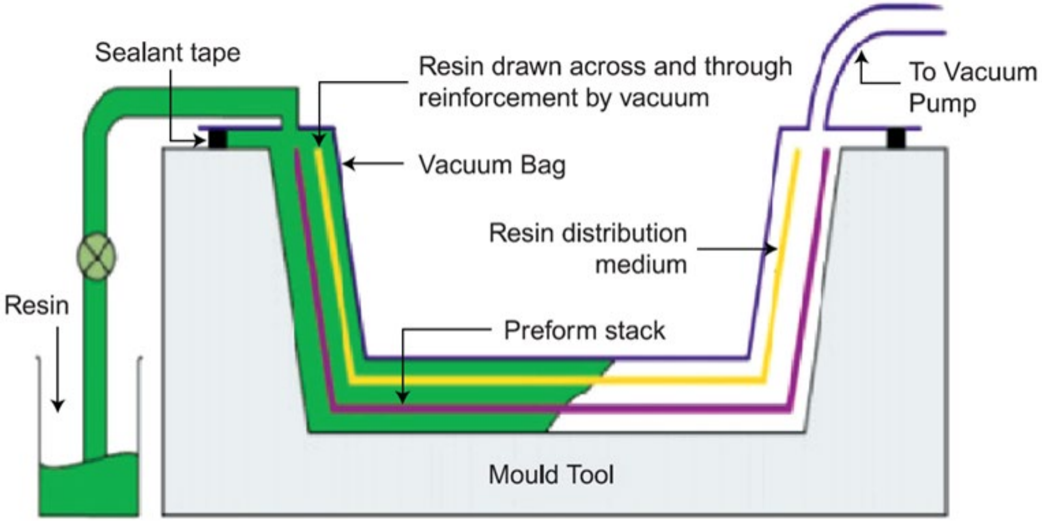
Integrate one or more AM powder handling techniques:

- piston or hopper feed
- Roller spreading/packing
- Patterning
  - Inkjet binder
  - Mist binder and selectively dry
  - Selectively heat
    - Projection
    - Selective absorption
- Repeat to allow for multiple powder materials

Selective Resin Infusion (SRI)

Heat under Vacuum to Infiltrate and/or Cure





SRI Infusion

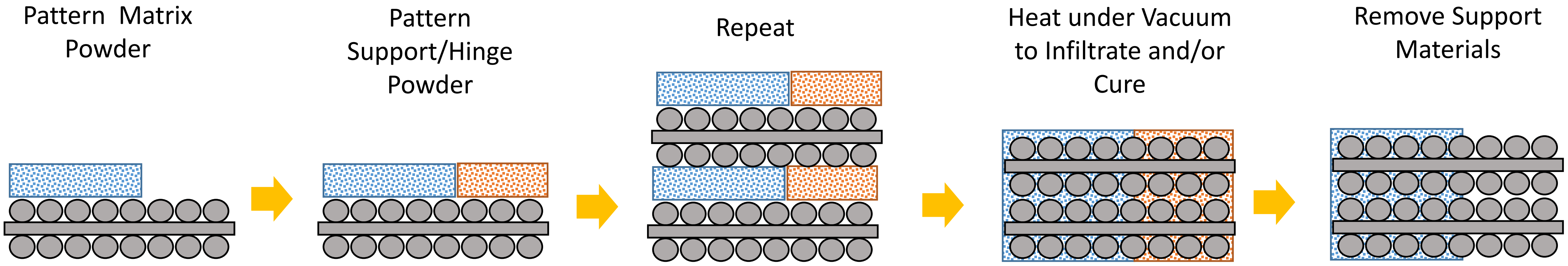
- Short infusion distances
  - order of the ply thickness
- Infiltration is more predictable because it is always through the ply thickness
- Multiple infiltrants can be used in one part
- Different types of sheets can be combined

Traditional Vacuum Infusion

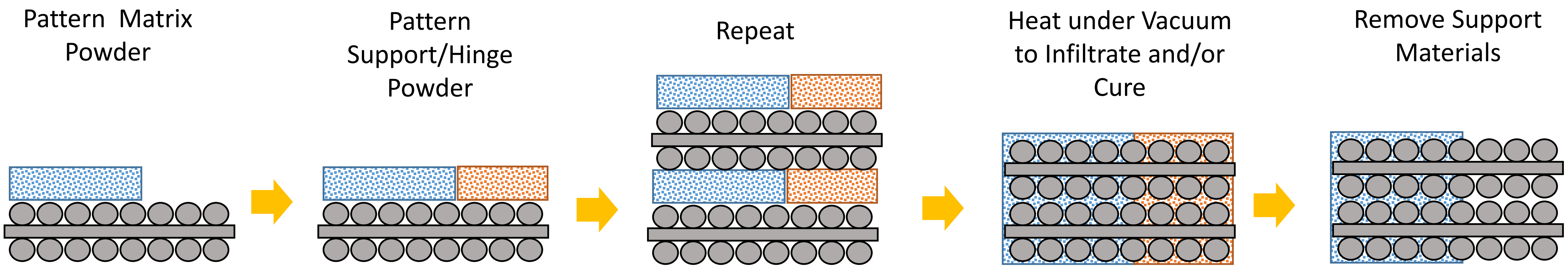
- Long infusion distances
  - order of the part size
- Requires expertise (and experiments) to optimize infiltration
- Can only infiltrate a single material

Image: https://www.nal.res.in/en/techniques/vacuum-enhanced-resin-infusion-technology

Selective Resin Infusion (SRI)



Continuous-fiber Composites by Selective Resin Infusion (SRI)

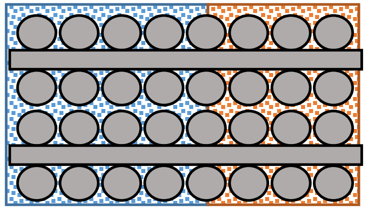


Key Features:

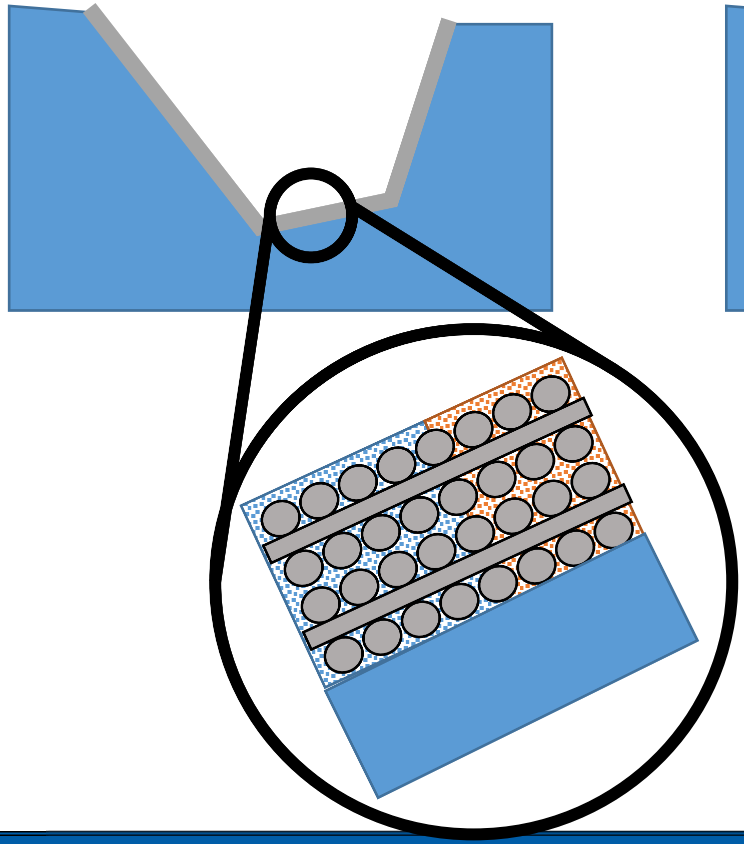
- Replace liquid resin with powdered resin
- Utilize AM methods to control quantity and location of resin
- Provide for multiple matrix materials
  - Spatially vary properties
  - Removable supports
  - Add functionality (sensing, electronics)
- Utilizes any powder matrix
  - Epoxy
  - Thermoplastic
  - Elastomers
- Can separate the infiltration and cure steps

Selective Resin Infiltration (SRI) Derivatives

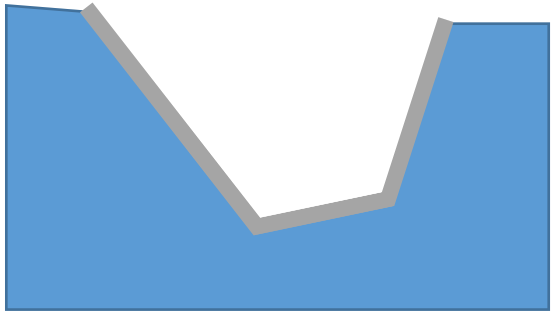
Heat under Vacuum to Infiltrate without Cure (B-stage)



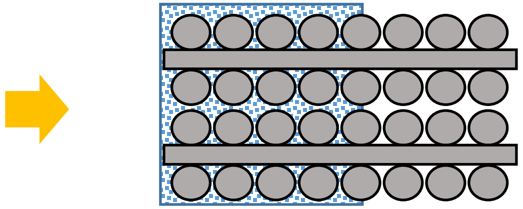
Bend or Form to final shape



Heat for final cure (cross link)

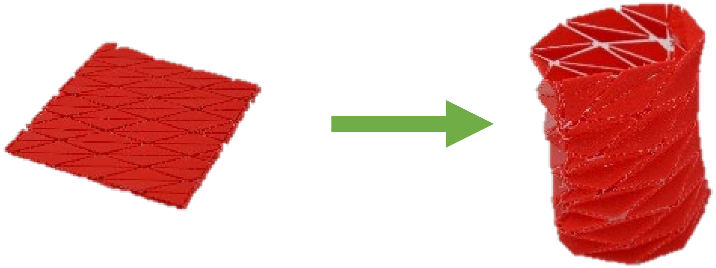


Remove Support Materials



Allows for improved fiber alignment of AM composites.

Applications



- High Performance Composite Manufacturing
  - Aerospace applications
  - New multi-functional capabilities

- Rapidly deploying systems
  - Double-walled B-cured composites globally or in hinges
  - Inflate to deploy
  - Possible Applications
    - Forward operating bases
    - UAV's
    - Force Protection

- Origami Manufacturing

Origami in Engineering

FIGURE 5 - FOLDING LITHIUM-ION BATTERY USING MIURA-ORI CREASE PATTERN [13]

FIGURE 10 - STEEL STENT GRAFT MODELS [22]

FIGURE 14 - CARDBORIGAMI SHELTER [24]

FIGURE 31 - FOLDING TOOL RACK/WORKBENCH [53]

E. Morris, et al., ASME DETC 2016

Origami in Engineering

FIGURE 34 - EMERGENCY BRIDGE IN FOLDED AND DEPLOYED CONFIGURATIONS [58, 59]

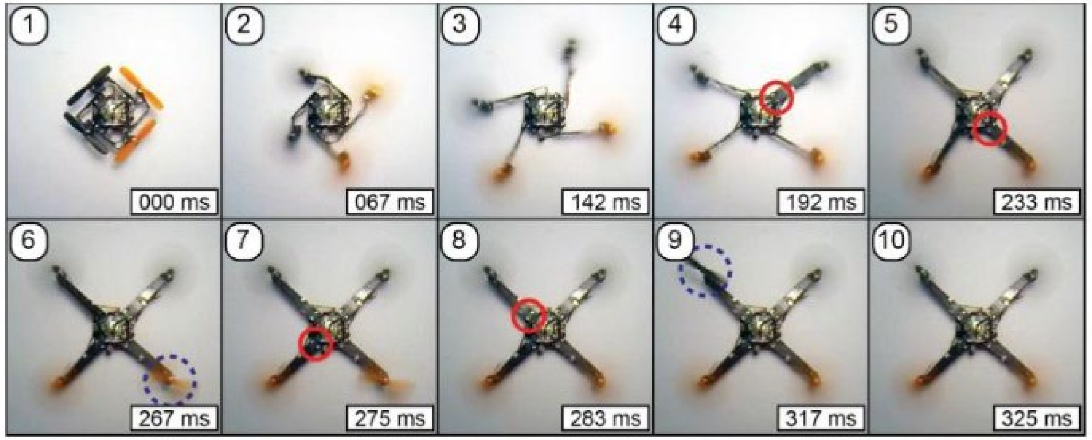


FIGURE 37 - DEPLOYMENT PROCESS OF QUADROTOR ARMS [66]

E. Morris, et al., ASME DETC 2016

Origami

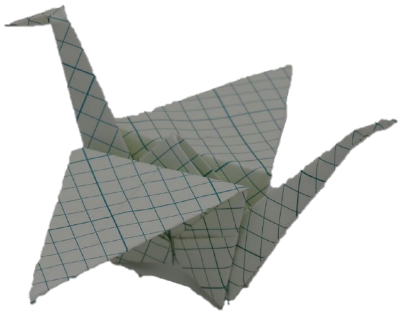
Benefits

- Compact forms that can deploy to large sizes
- Leverage strengths of 2D materials

Challenges

- Manufacturing is difficult
  - Limits to simple devices and/or low volumes
- Current materials have low performance

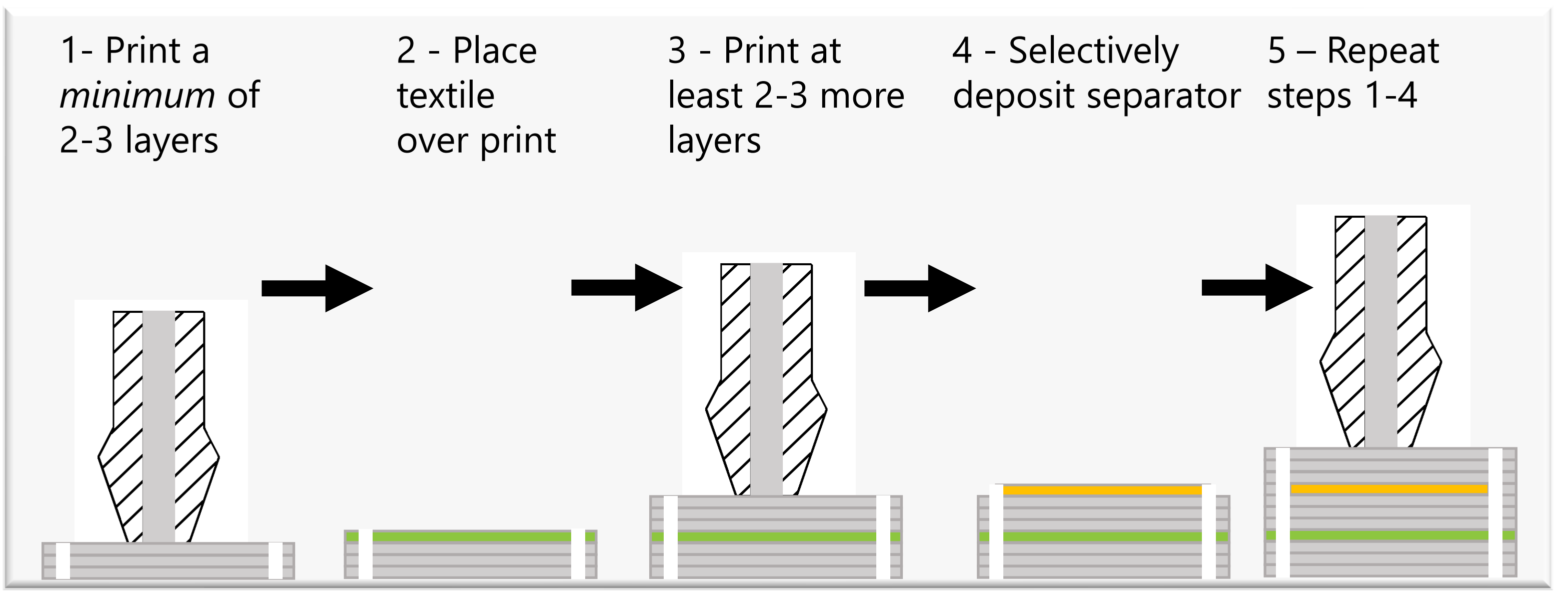
Manufacturing Origami



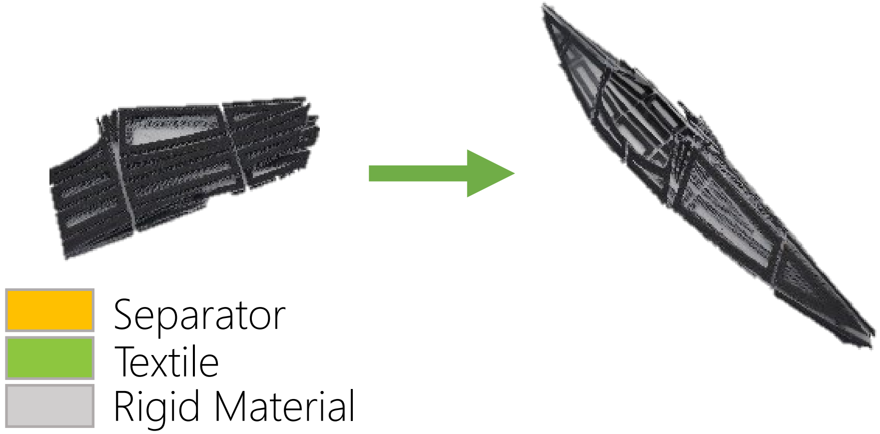
Paper Crane –What is easy in paper, is hard in engineering materials

Currently origami manufacturing currently relies on one-off solutions and extensive hand labor

BYU Embedded Textile Method



BYU approach to 3D Printing origami increases automation, provides digital control of shapes, and allows for compact manufacturing of shapes that later deploy.

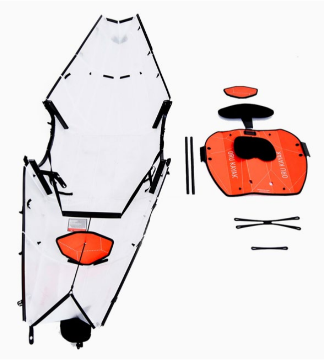


Multi-Planar Origami

Traditional

$$f : \mathbb{R}^2 \to \mathbb{R}^3$$

Starts flat and is assembled into a complex 3D shape



Multi-Planar Approach

$$f : \underbrace{\mathbb{R}^2 \times \mathbb{R}^2 \times \cdots \times \mathbb{R}^2}_{n} \to \mathbb{R}^3$$

Series of flat components that then expand into 3D shapes

n represents the number of planes

n= 7

Multiplanar fabrication allows for:

- Closed containers
- Compact Manufacturing in small build spaces

Applications

- Changing approach to Manufacture of Large Systems
- Benefits in Construction
  - Reduce skilled labor
  - Replace steel reinforcement with external fiber reinforced systems
    - Lighter, lower carbon footprint, reduce concrete requirement
  - Centralized manufacturing with on-site deployment
  - Digital manufacturing enables enhanced optimization
  - Optimize the performance while maintaining simplicity of deployment
- Lower cost of high-performance deployable systems
  - Solar arrays (space and terrestrial)
  - Low cost attritable aircraft
- Embed functionality into the layered system
  - Deployment
  - Energy Storage
  - Sensing

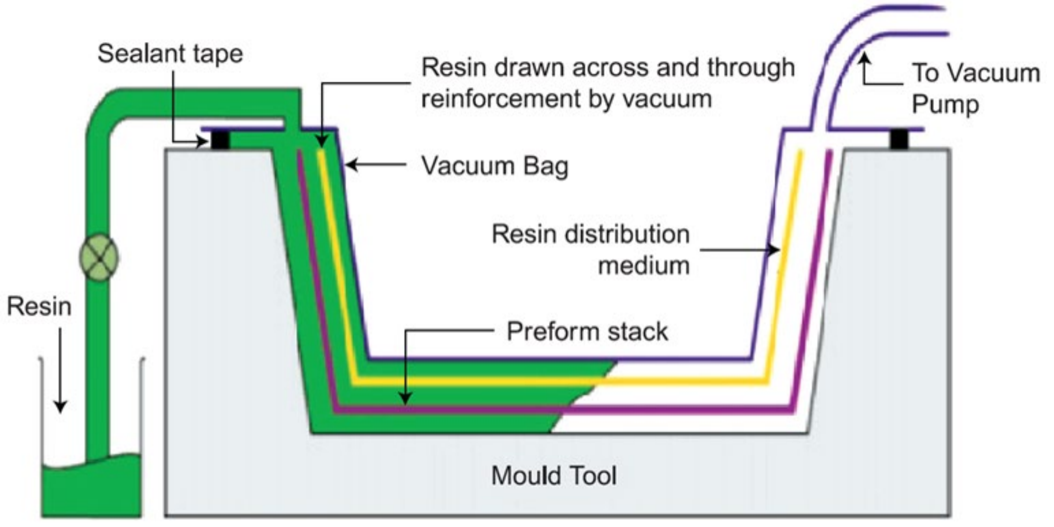
Research Tasks

- Develop integrated thermal and flow models for infiltration into woven materials
- Characterize the interface between adjacent materials
- Develop methods of controlling the interface between multiple materials
  - Competitive infiltration
  - Wetting agent changes
- Build a scale-model production system to evaluate build speeds and identify quality control needs and methods
- Integrate automatic fiber trimming

Conclusions

- Selective Resin Infiltration (SRI) offers
  - Simple design with through ply infiltration
  - High fiber content with oriented fibers
  - Integrated, removable supports for more complex geometry
  - Can infiltrate and then form to quickly create complex 3D shapes
- SRI is well-suited for origami fabrication
  - Directly fabricate hinges
  - Supports Multiplanar origami for compact fabrication
  - Potentially integrate additional functionality
    - Actuation, sensing, energy storage, etc.

Traditional: Infiltrate along the ply



SRI: Through Ply Infiltration