

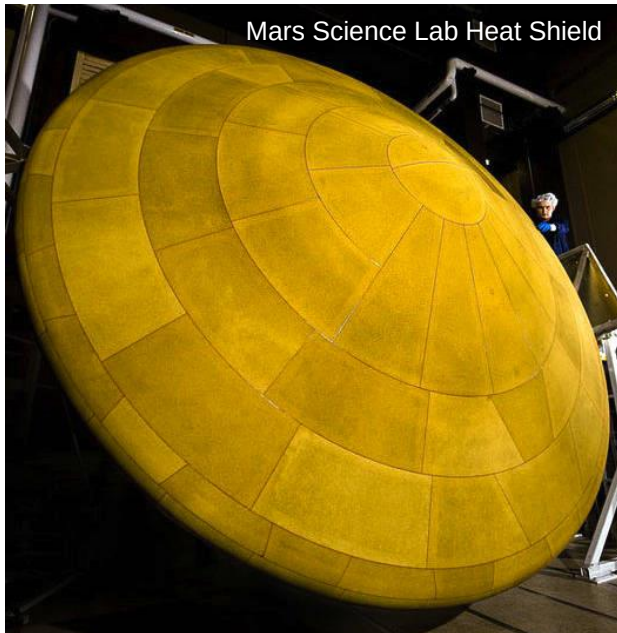
Additive Manufacturing of Nanomaterial Based Hierarchical Structures



WILLIAM & MARY

CHARTERED 1693

Motivation



- Mars mission gear ratio = 1000
- Improve current systems to enable new missions
- Lighter material, fewer materials, less material



Launch Mass = 2.5×10^6 kg

Landing Mass = 2500 kg

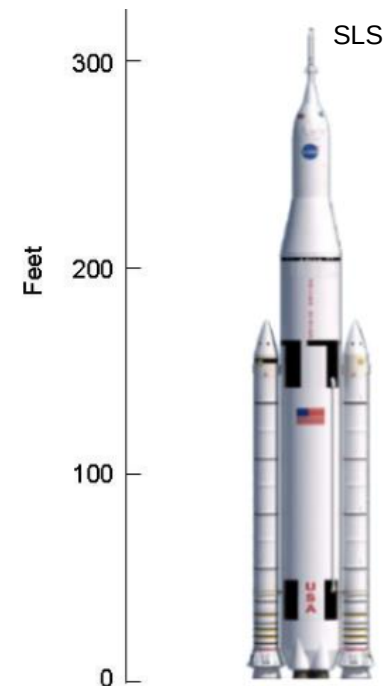
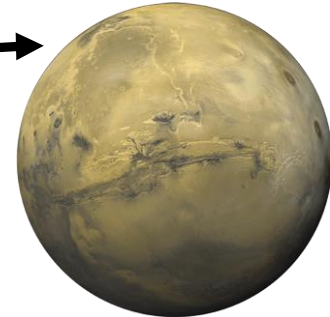
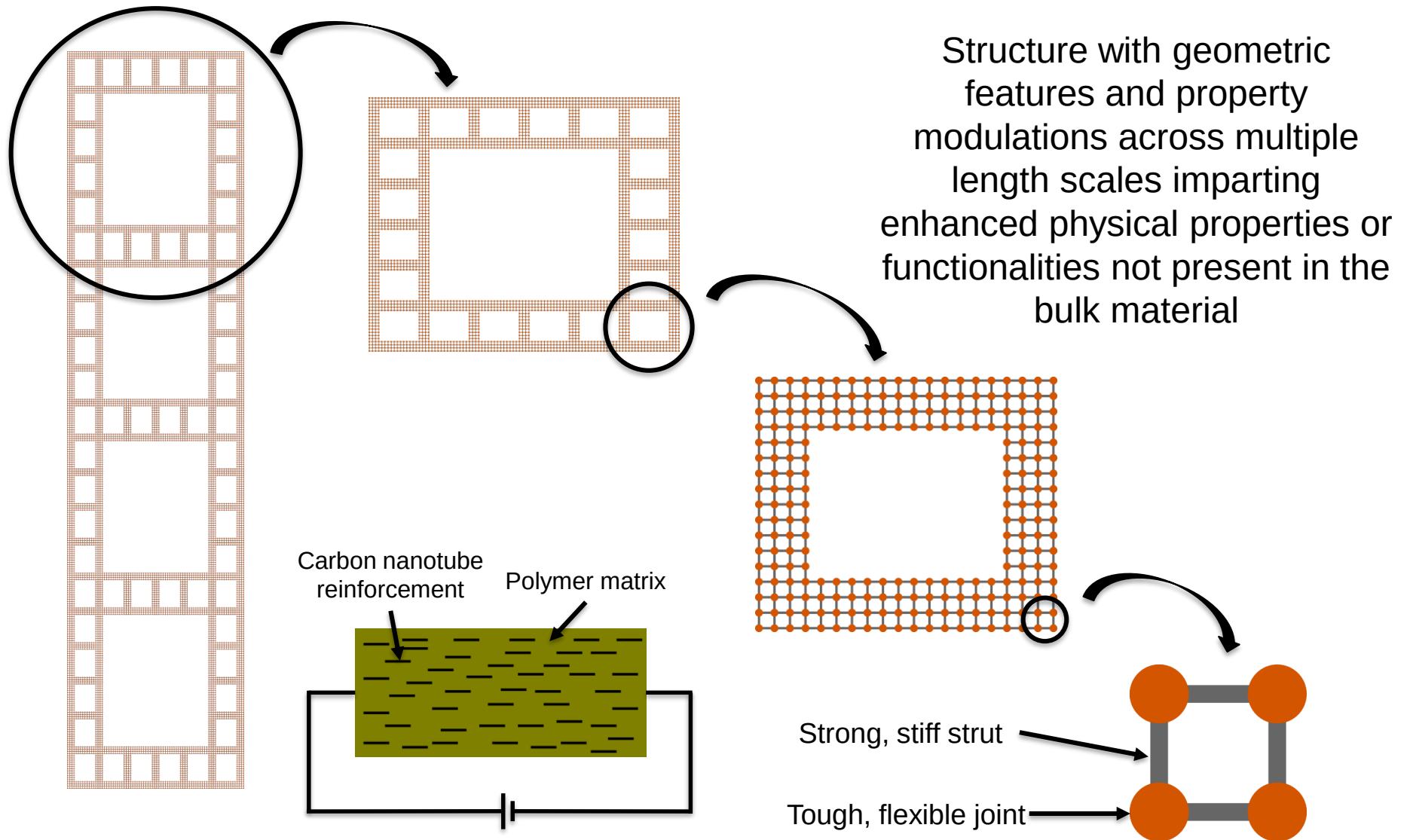
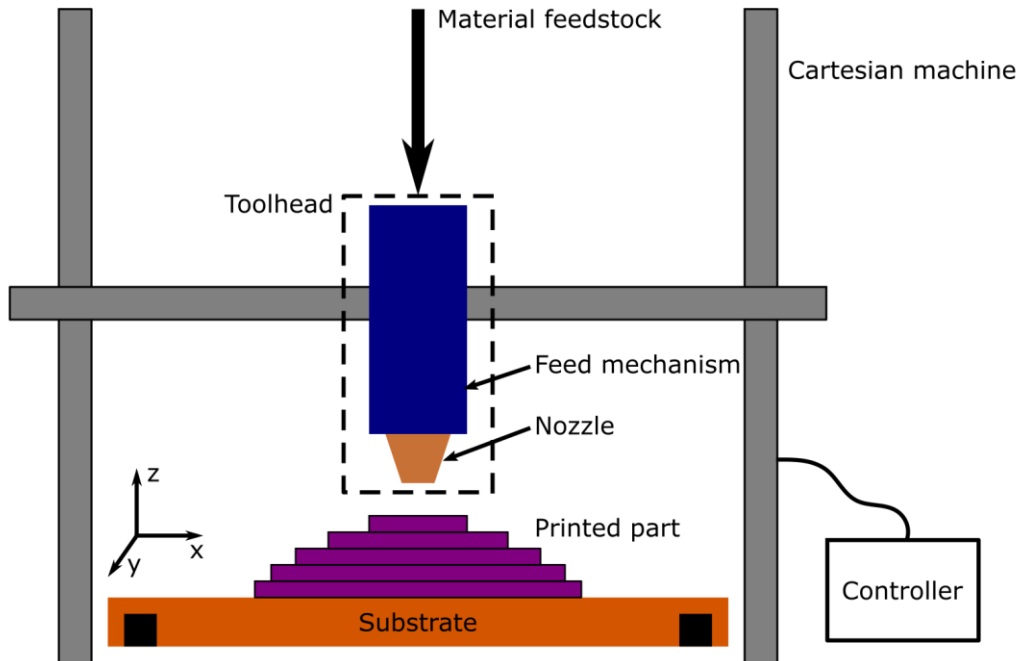


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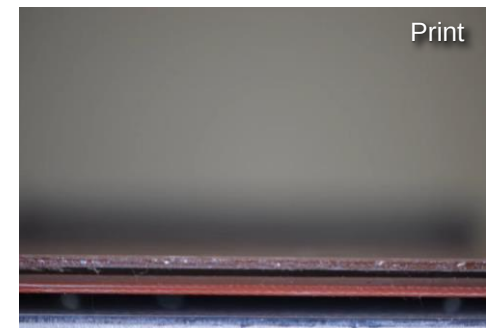
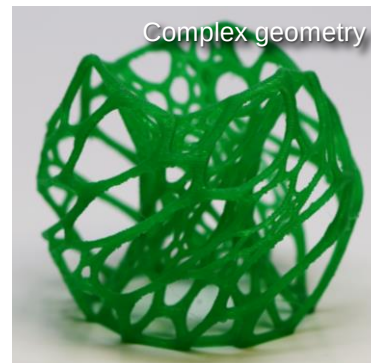
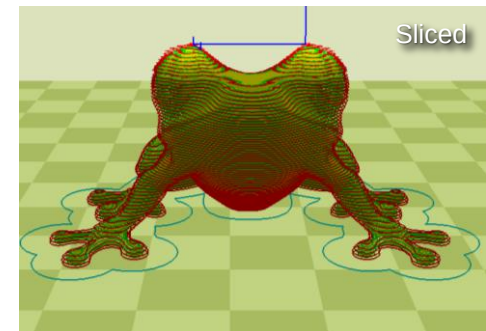
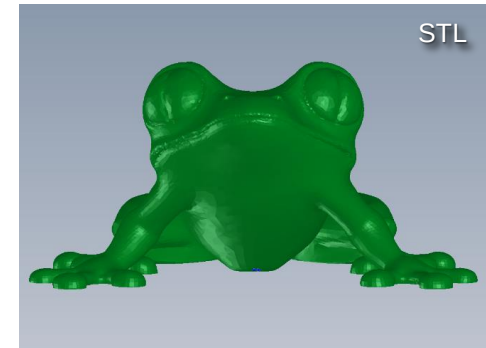
Hierarchical Structures



Additive Manufacturing



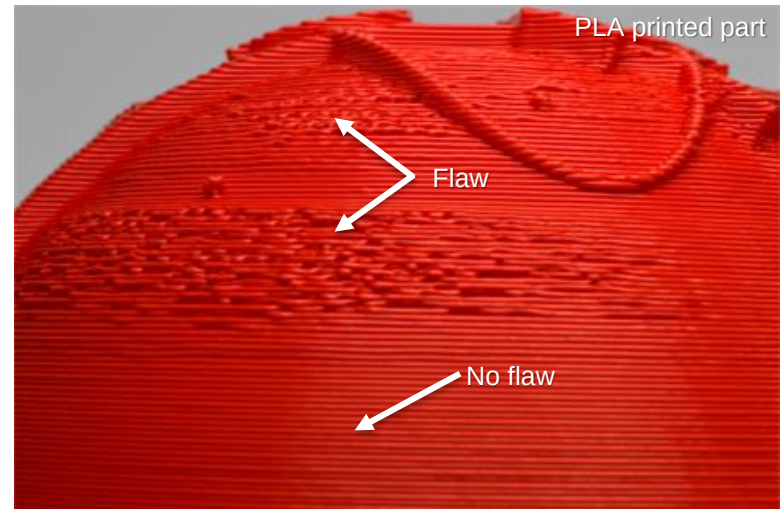
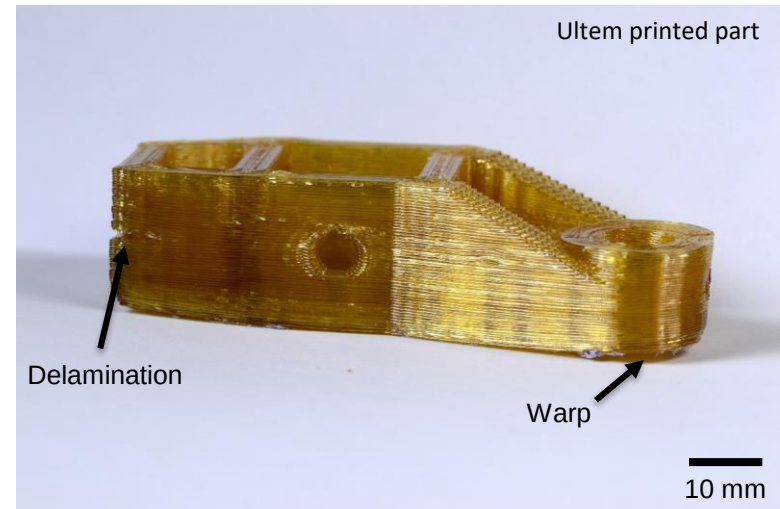
- Layer-by-layer process
- Fewer geometric constraints
- Selective material deposition
- Extrusion-based methods
 - Fused Filament Fabrication
 - Syringe pump



Additive Manufacturing

Issues

- Material specific
 - Parameters and machine depend upon material
- Repeatability
 - Ideal parameter settings are different part-to-part and machine-to-machine
 - Difficult to predict part mechanical properties
- Part size/feature resolution
 - Resolution restricted by nozzle size
 - Large parts restricted by deposition rates (i.e. print time)



Objective

Accelerate adoption of 3D printing in aerospace by investigating issues involving part quality, material compatibility, and hierarchical structures.

Outline

Part Quality and Repeatability

Material Hierarchy

Geometric Hierarchy

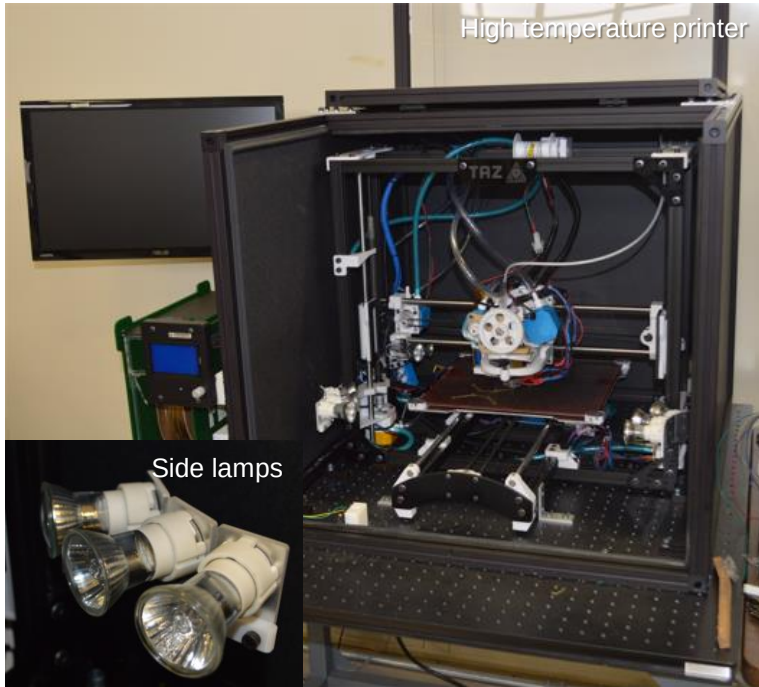
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Part Quality and Repeatability

Material Hierarchy

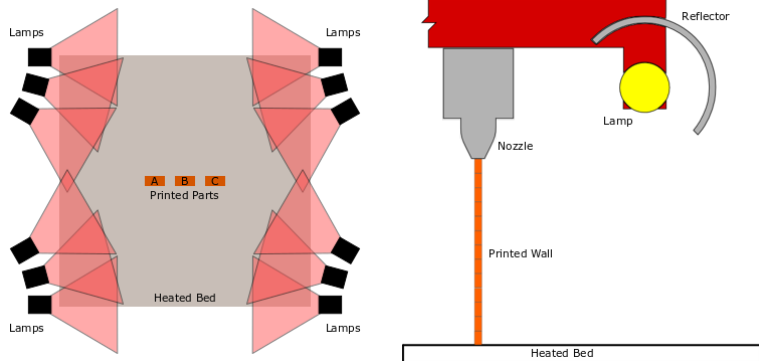
Geometric Hierarchy

High Performance Thermoplastics

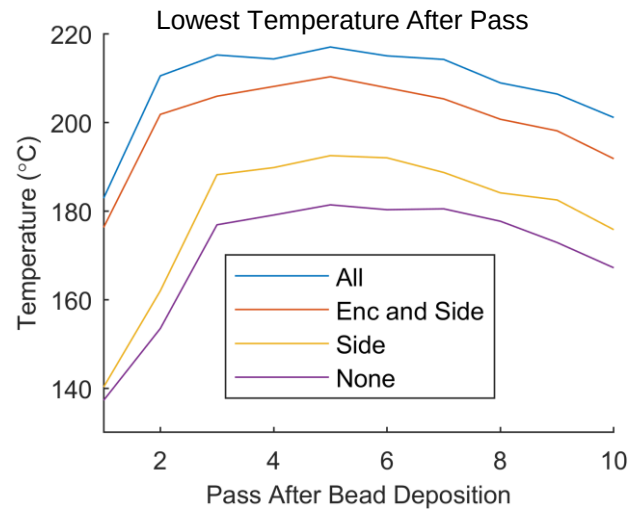
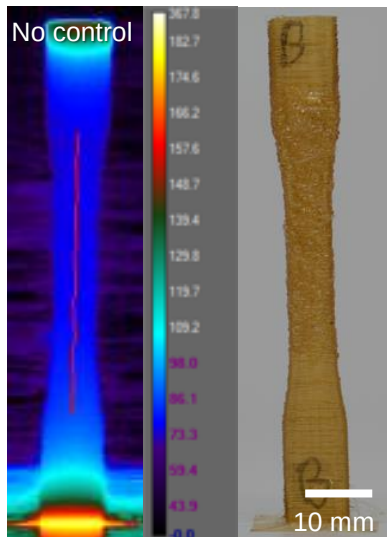
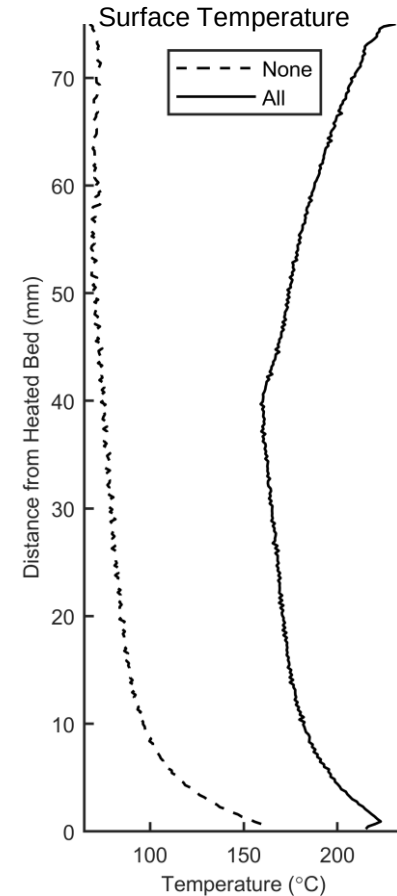
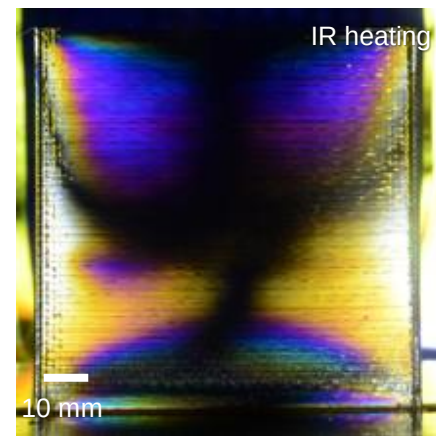
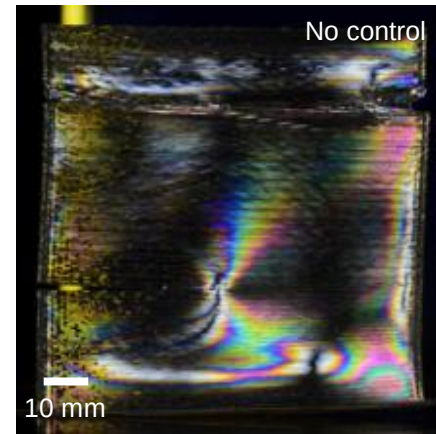
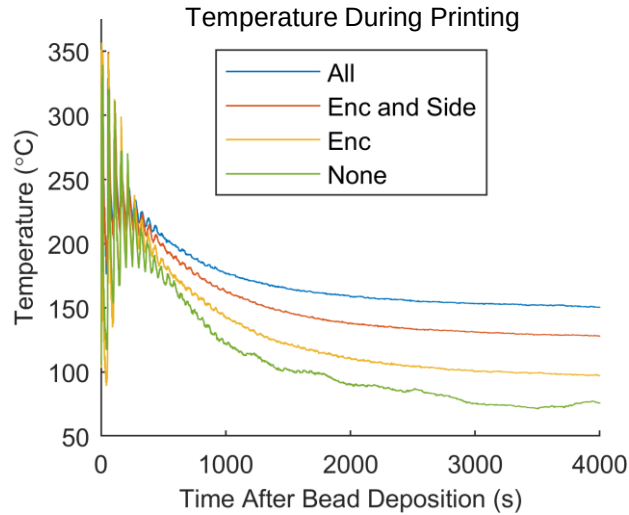
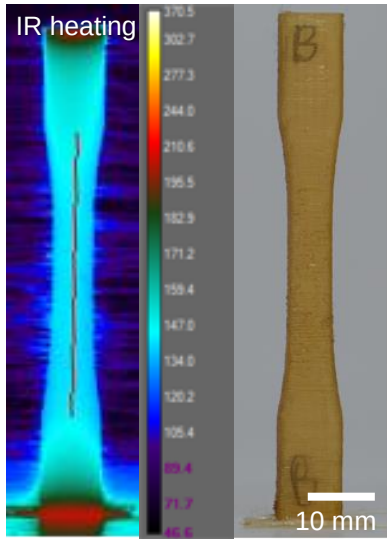


- Understanding of printing parameter effects on parts necessary to improve consistency and quality
- Industrial machines lack adjustability needed for experiments
- Open-source machines not designed to function at settings required for high performance materials
- Develop IR based heating system to directly control part temperature
- Validate method and explore effects on part mechanical properties and quality

Lamp Layout

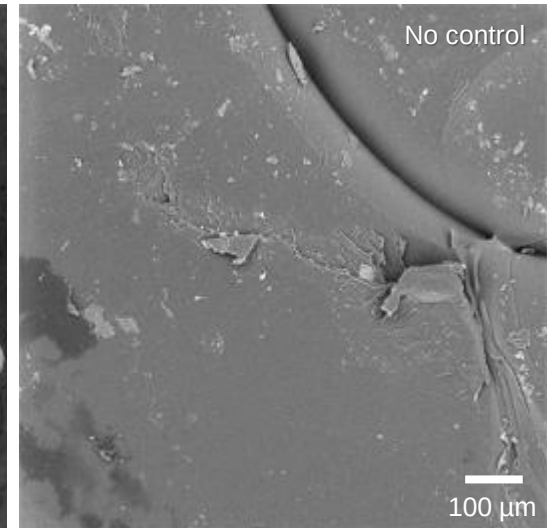
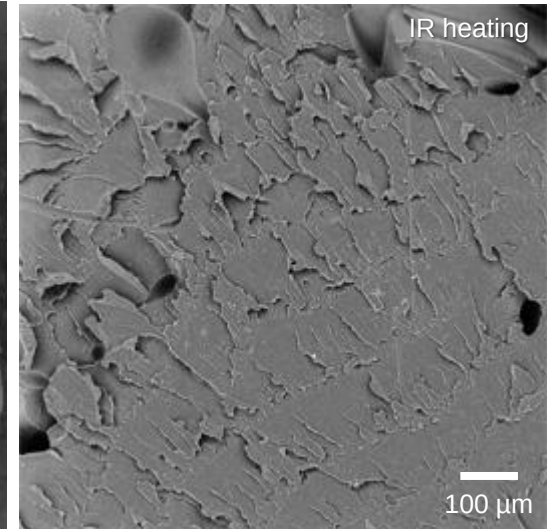
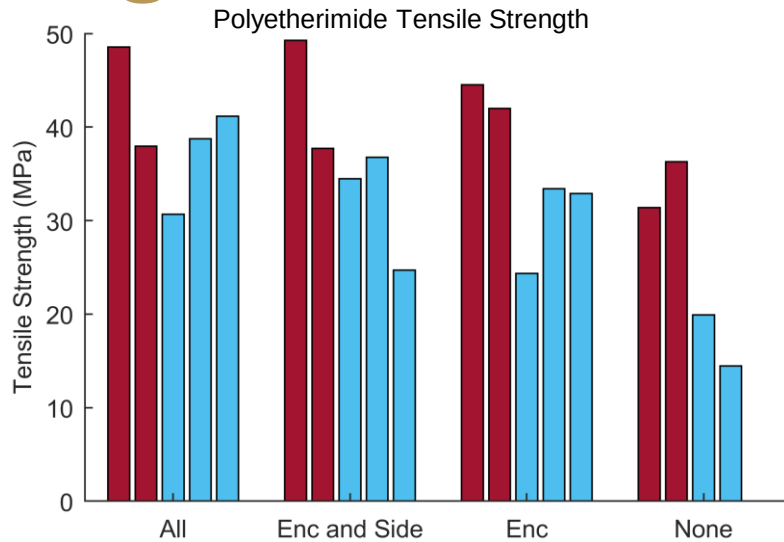


High Performance Thermoplastics



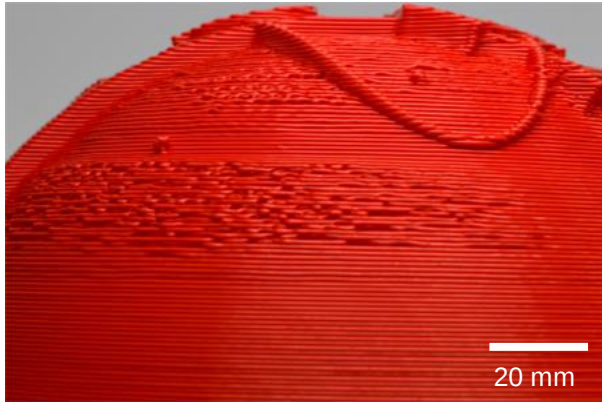
- Surface temperature jump with addition of controls
- Reduction in residual stress

High Performance Thermoplastics

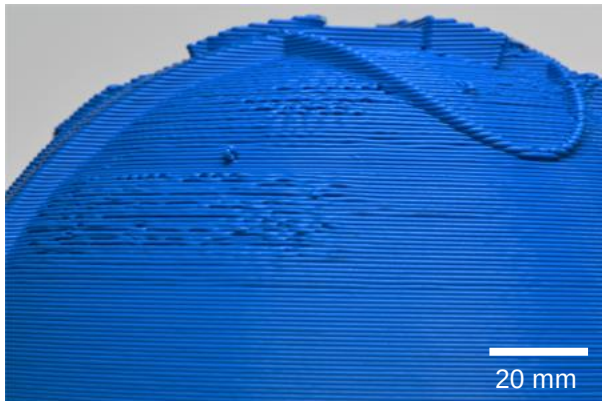


- IR heating improves part surface quality and helps to prevent flaws
- Part temperature not critical to strength of part after a certain point
- Overall mechanical properties inconsistent and dependent on location in print as much as environmental controls

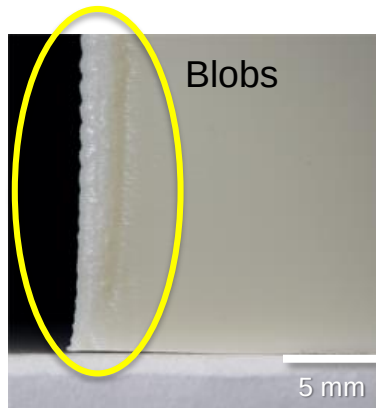
Print Parameter Setting Optimization



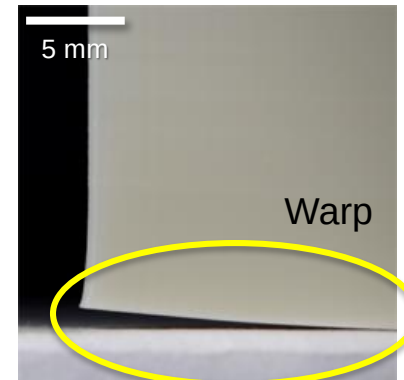
Change material



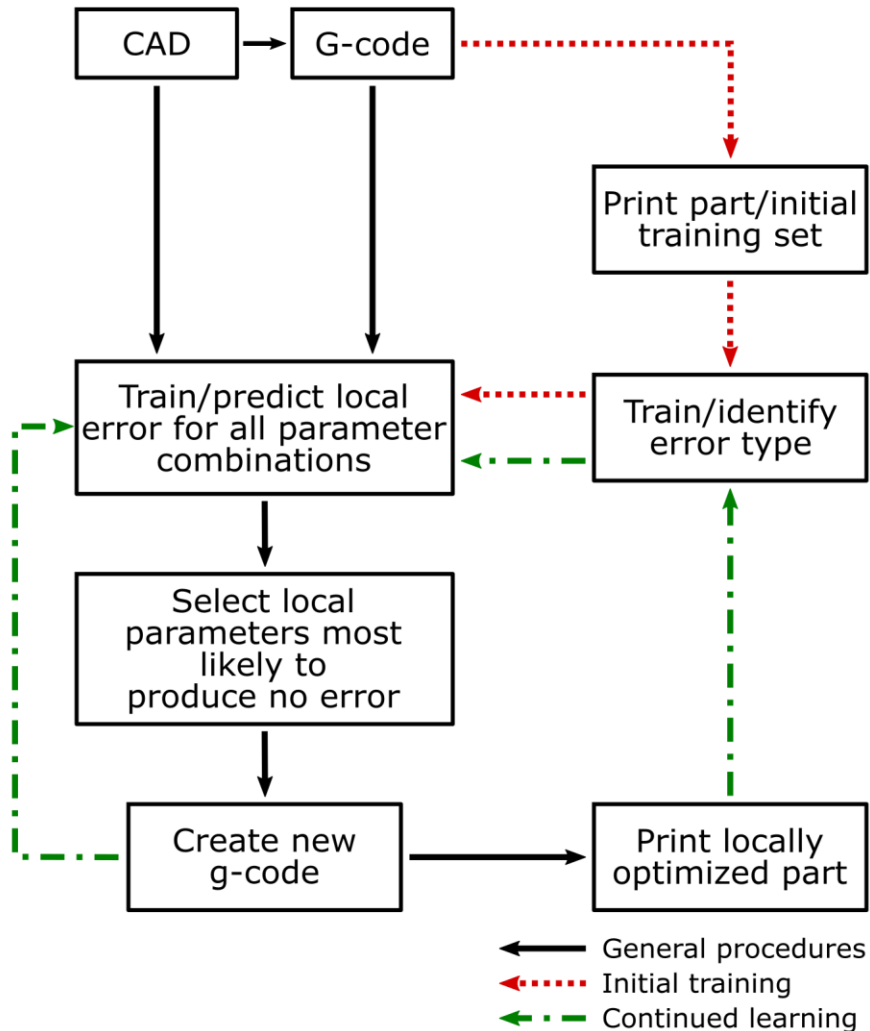
- Mechanical properties dependent upon location in the part
- Systematic flaws occurs from part-to-part
- Adjusting global parameters can cause new errors
- Print parameter settings need to be selected at a local level



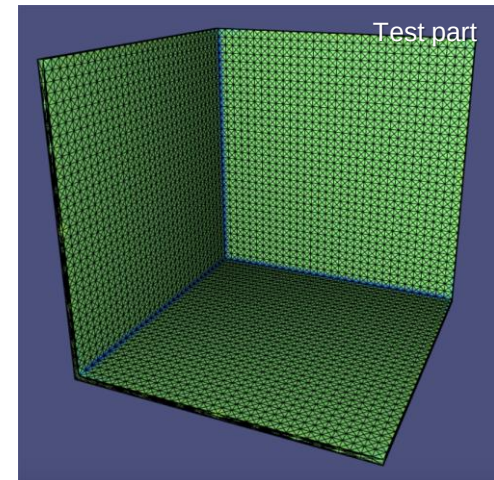
Adjust global parameter settings



Print Parameter Setting Optimization

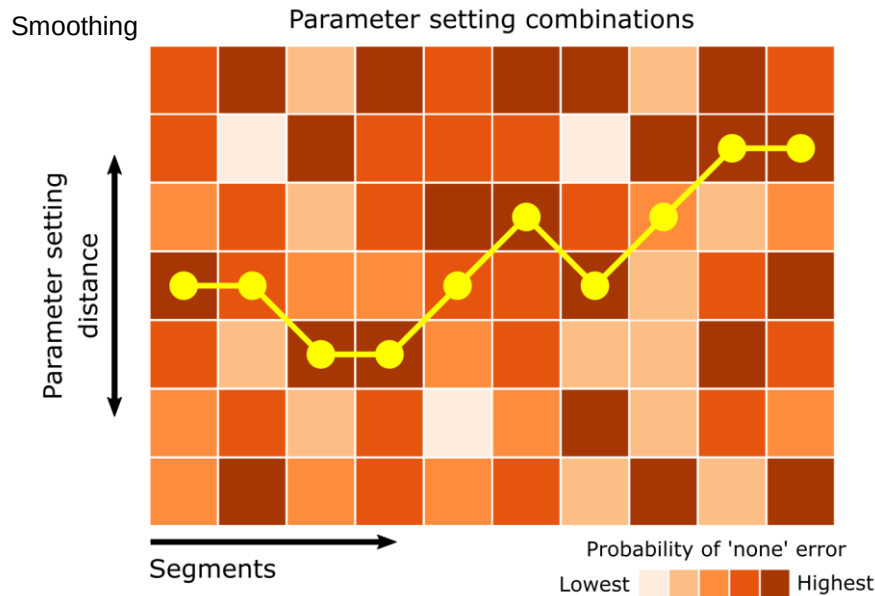
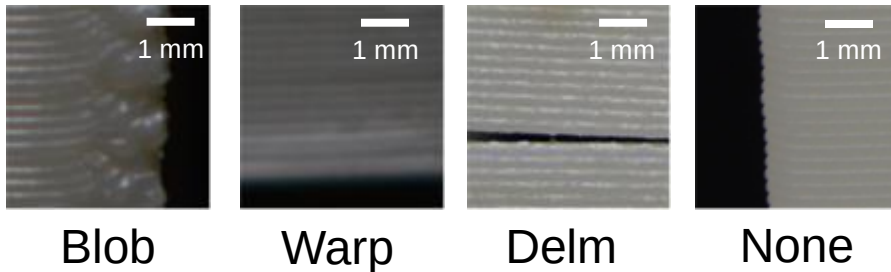


- Develop method based on machine learning to optimize parameter settings based on location in part
- Modular system that can be modified depending on process, data collection, etc
- Simplify problem: basic part geometry, data collection, and errors (blobs, warps, delaminations, and 'none')



Print Parameter Setting Optimization

Flaw Types



- Detect errors: Image part, train, and detect errors via transfer learning (AlexNet)
 - Overall accuracy: 98.26%
- Predict errors: Predict probability of errors occurring for future setting combinations
 - Overall accuracy: 73.69%
- Select and smooth local parameter settings for optimum quality

Error Detection

0 1.00

True flaw \ Predicted flaw	Blob	Warp	Delm	None
Blob	0.87	0.03	0.08	0.03
Warp	0.00	0.98	0.00	0.03
Delm	0.00	0.00	1.00	0.00
None	0.00	0.00	0.03	0.98

Flaw Prediction

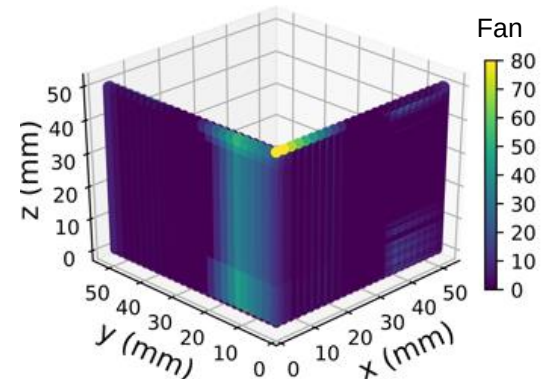
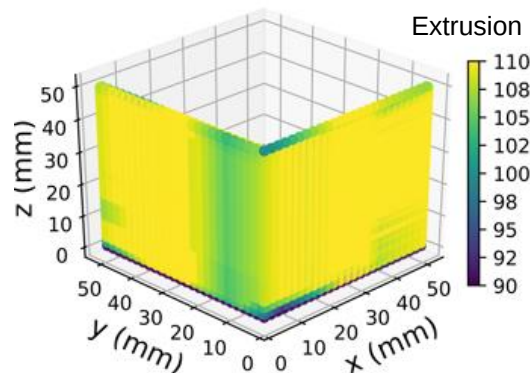
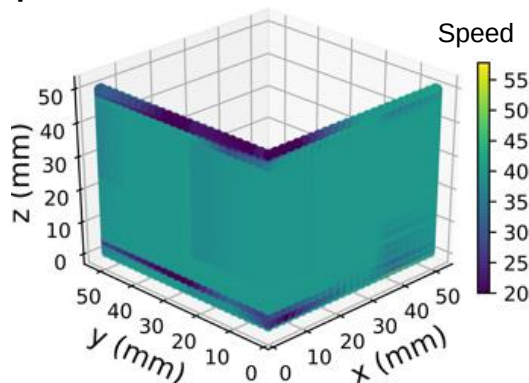
True flaw \ Predicted flaw

	Blob	Delm	None	Warp
Blob	0.73	0.12	0.05	0.10
Delm	0.01	0.89	0.02	0.08
None	0.01	0.14	0.76	0.09
Warp	0.08	0.18	0.08	0.66

0.0 1.0

Print Parameter Setting Optimization

- System adjust parameters to produce highest quality part (as classified by the detection algorithm)
- Changes to parameter settings are coupled and similar to those done by a human
- System can adjust parameter settings in ways not possible using existing software
- System can be adjusted to user priorities



Print Parameter Setting Optimization

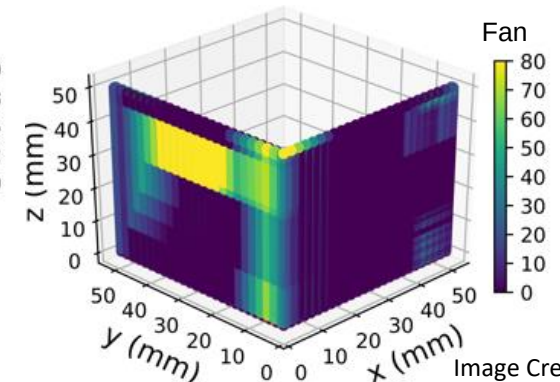
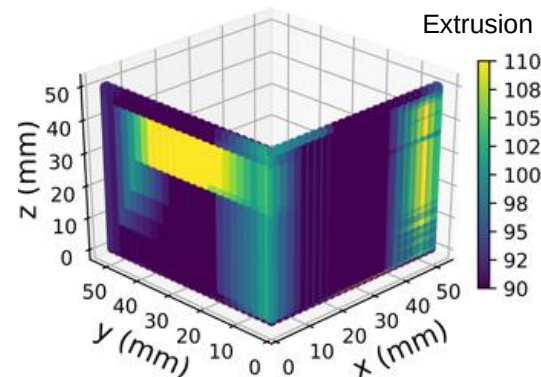
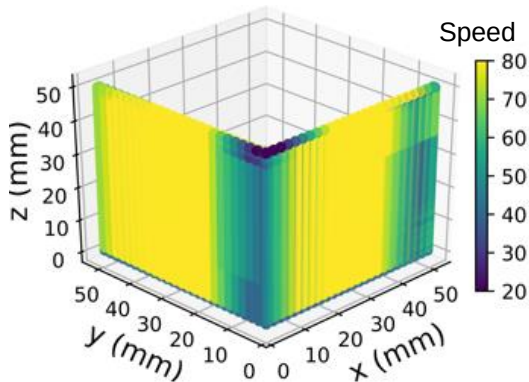
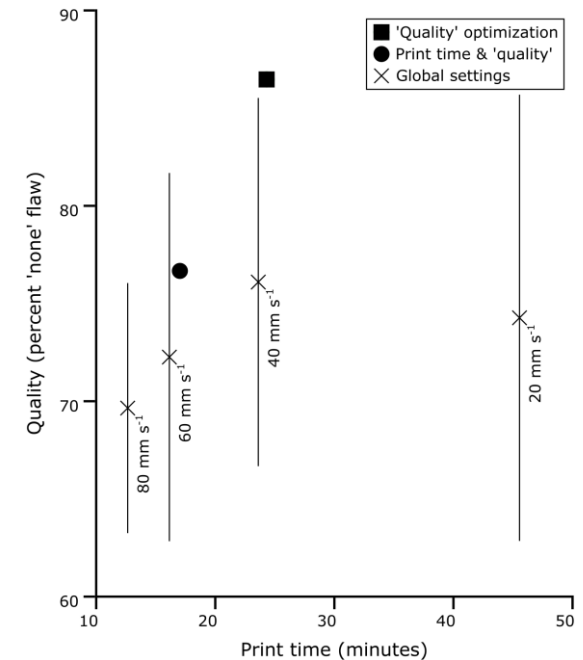
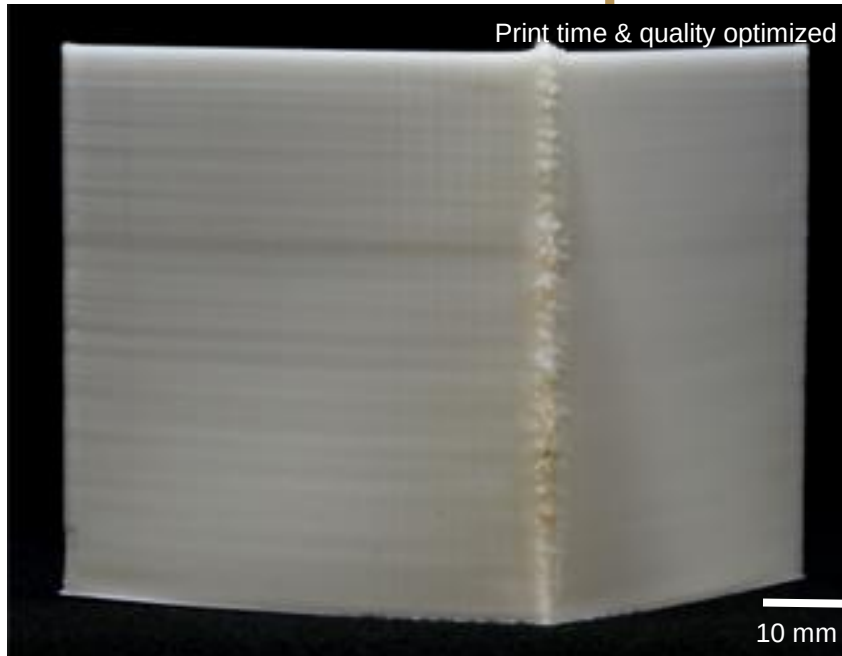


Image Credits: NASA

Outline

Part Quality and Repeatability

Material Hierarchy

Geometric Hierarchy

CNT Yarn Multifunctional Structures

Potential

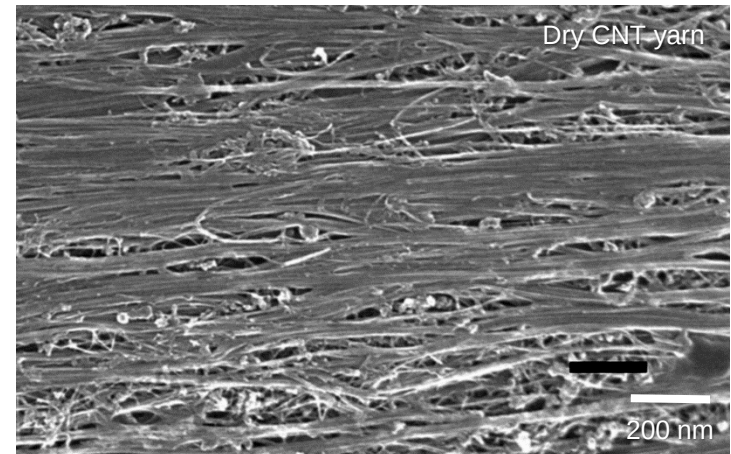
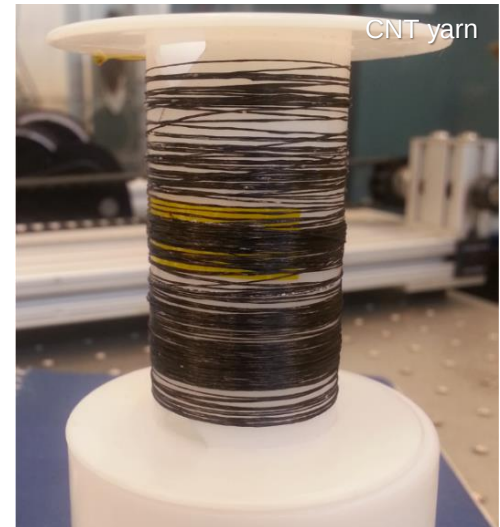
- Superior mechanical properties at the nanoscale
 - Multifunctionality: e.g. electrical and thermal conductivity

Challenges

- Scaling up while retaining material properties
- Handling difficulties
- Low CNT content (5% wt.)

CNT Yarn Printing

- High density aligned CNTs
- Use 3D printing to selectively place CNT yarn into polymer parts

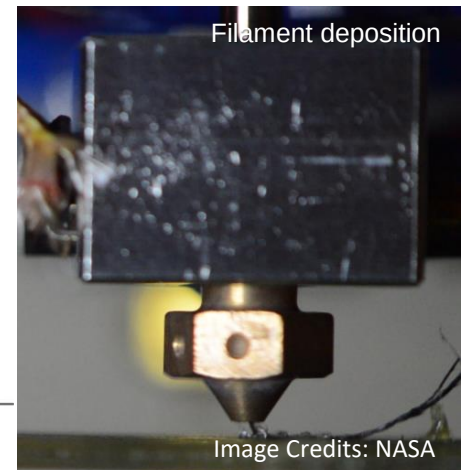
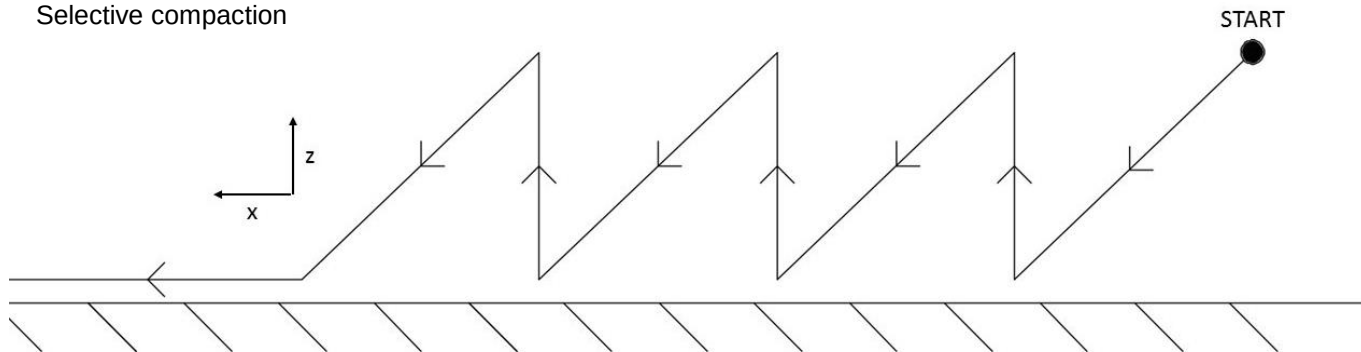


CNT Yarn Multifunctional Structures

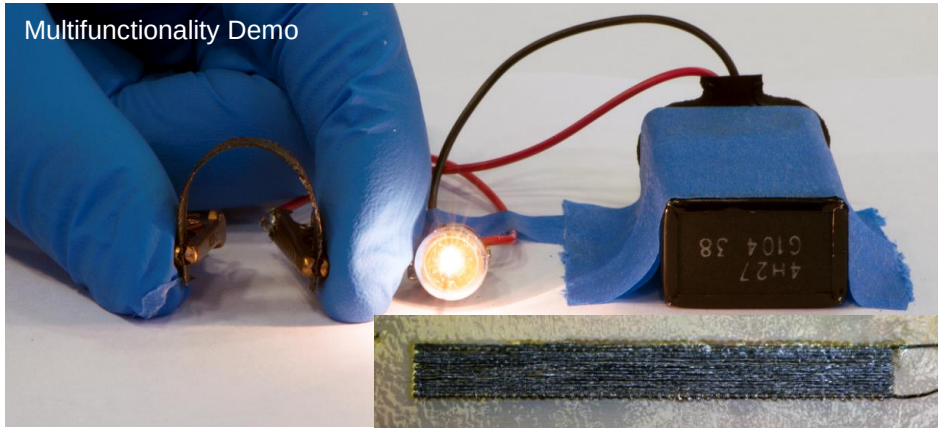
- High temperature printer with two print heads
- Polyetherimide (PEI) neat resin
- CNT yarn coated with PEI
- Yarn Printing: anchor, pull, cut
- Selective and continuous compaction depending upon use



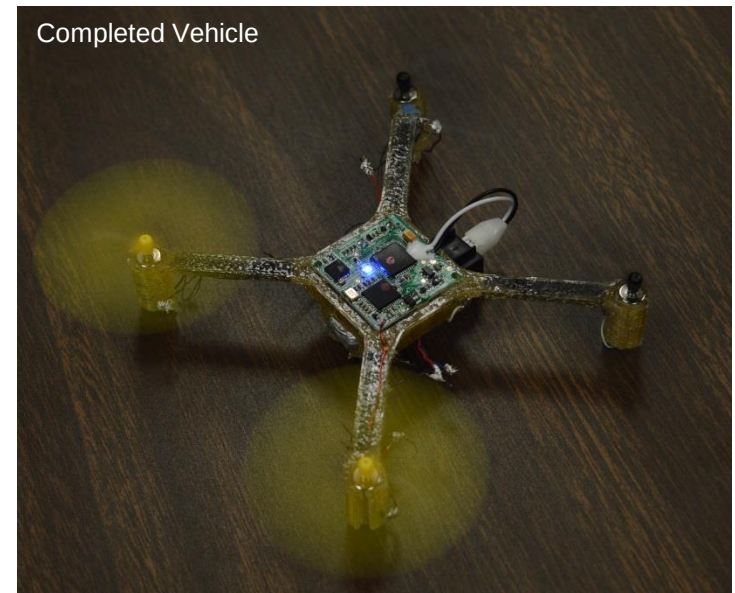
Selective compaction



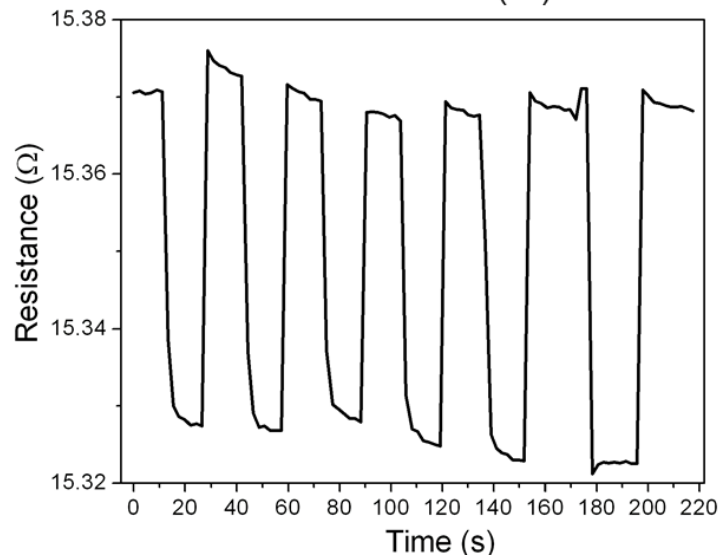
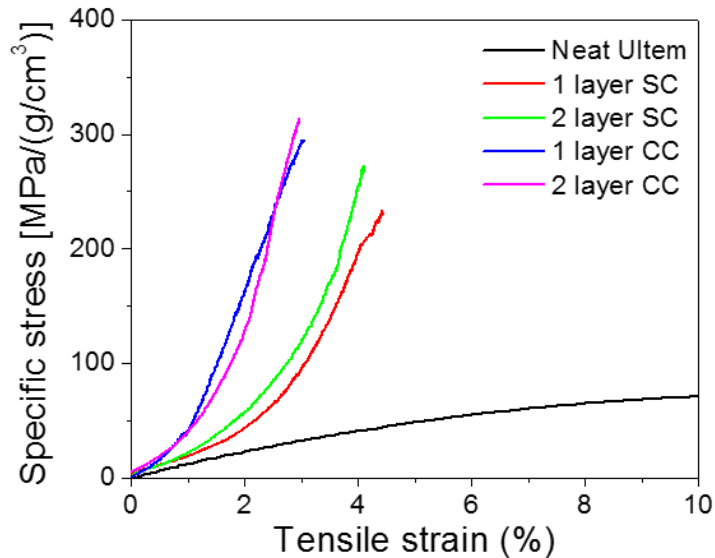
CNT Yarn Multifunctional Structures



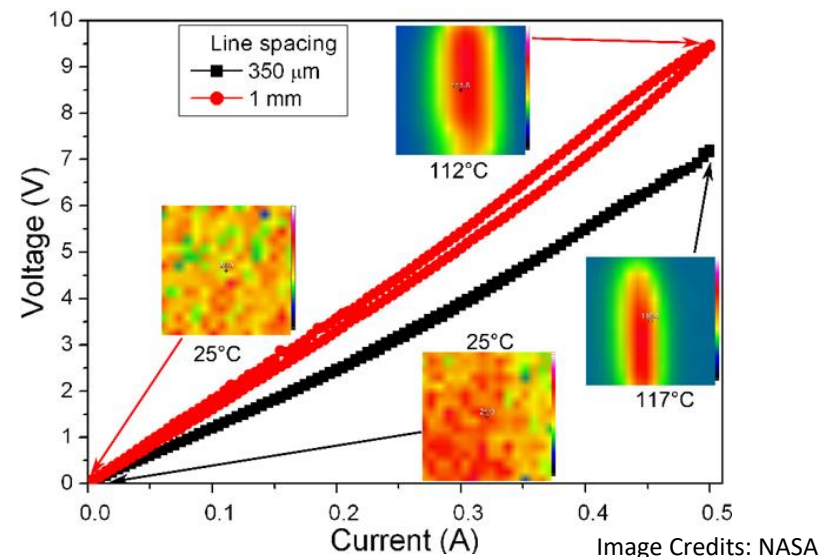
- Flexible conductor used to power lamp
- 'nAno' demo showing compliance of material
- Quadcopter with printed CNT yarn arms used to power motors



CNT Yarn Multifunctional Structures



- Selective vs Continuous
 - Tensile test of one and two layer samples
- Strain Sensor
 - Cyclical 3-point bending
 - 5 kg load at 5% strain
- Heating Element
 - Current cycled from 0-0.5 A



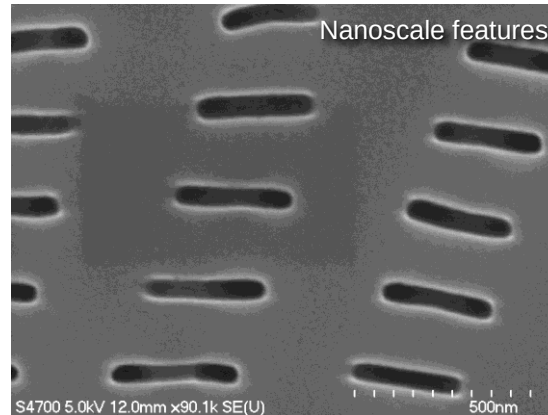
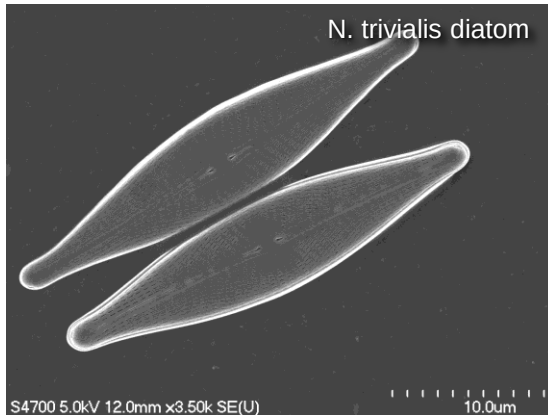
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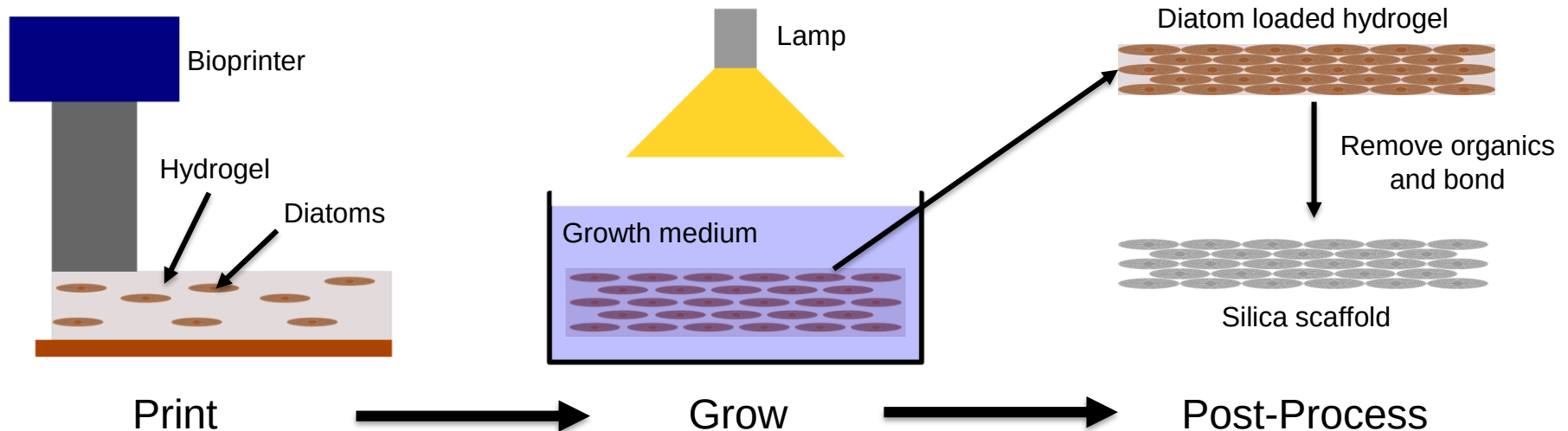
Material Hierarchy

Geometric Hierarchy

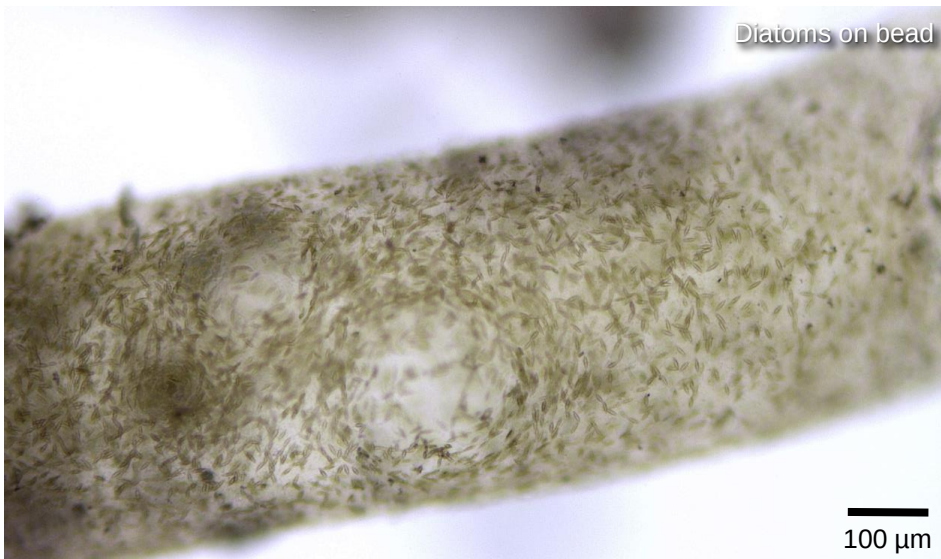
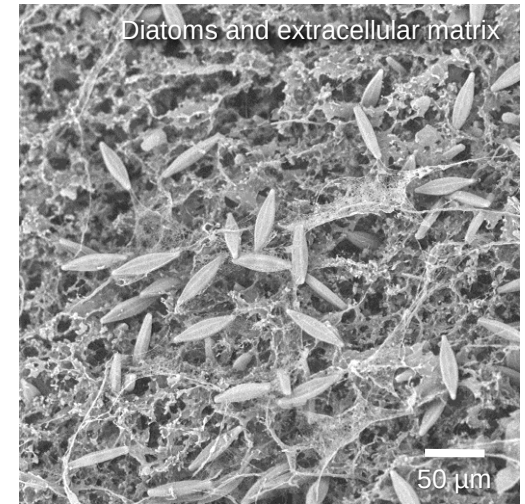
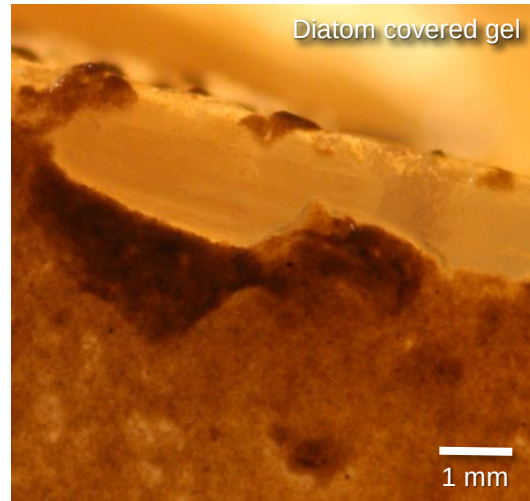
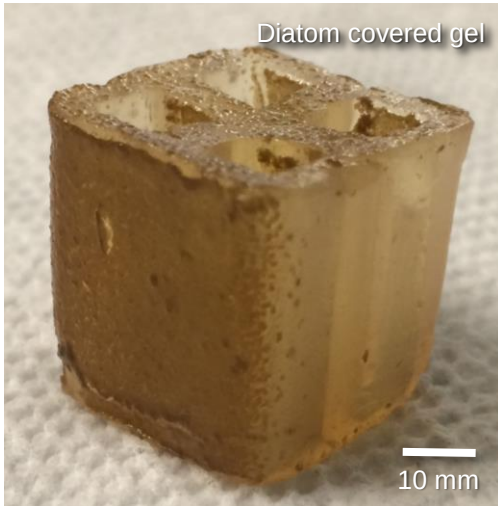
Diatom Bioprinting



- Diatoms contain nanoscale silica hierarchical geometries.
- Use 3D printing to place diatoms in select locations, allow diatoms to replicate and cover part, remove organics and bond to create silica scaffold.
- Need understanding of diatoms printability and growth characteristics.

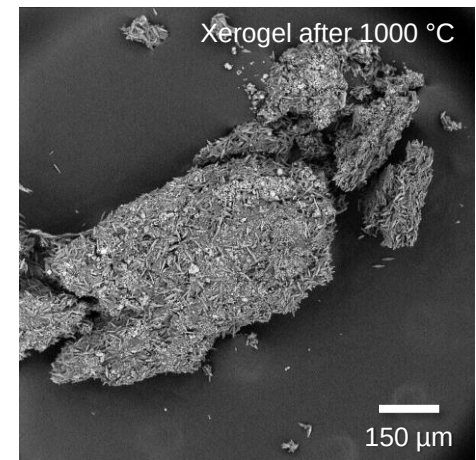
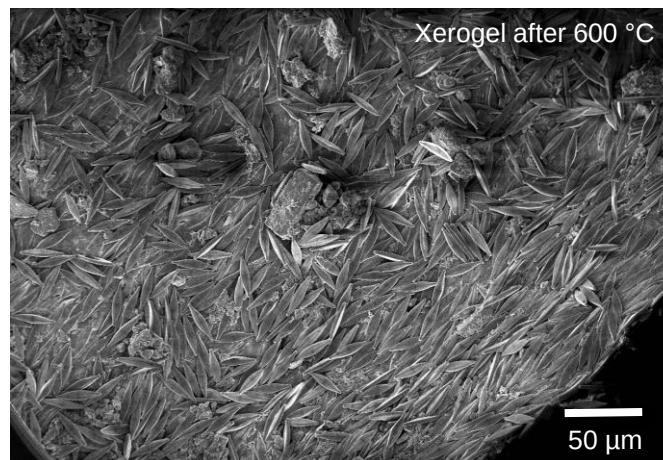
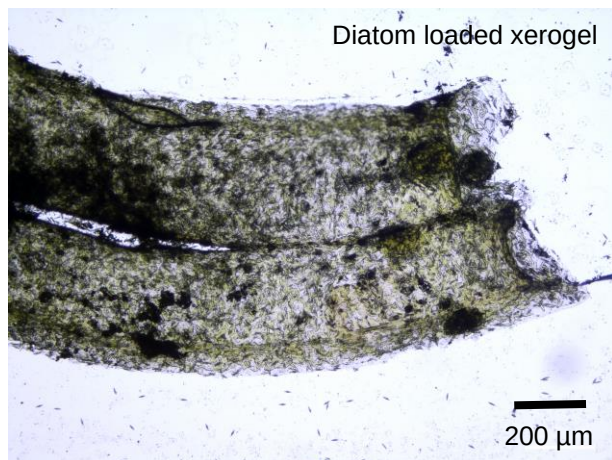
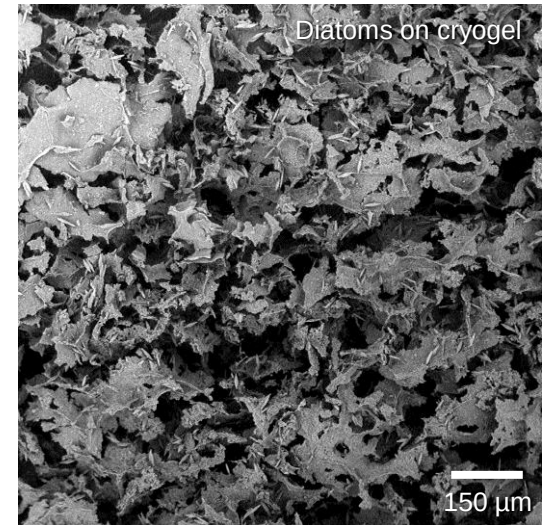
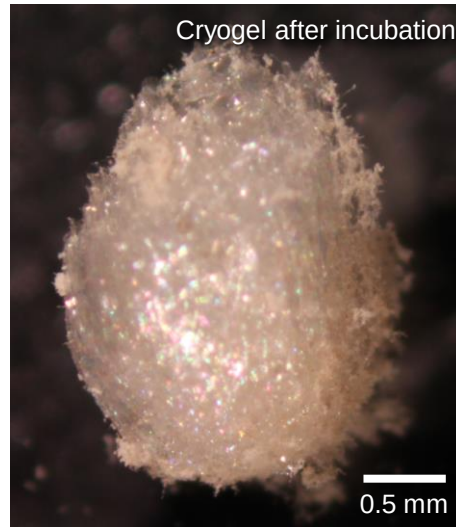
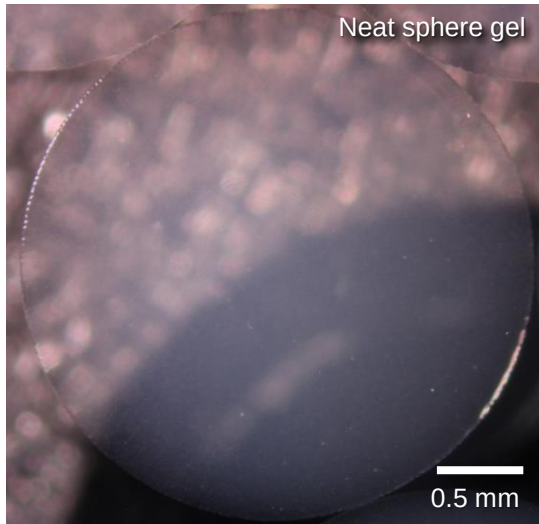


Diatom Bioprinting

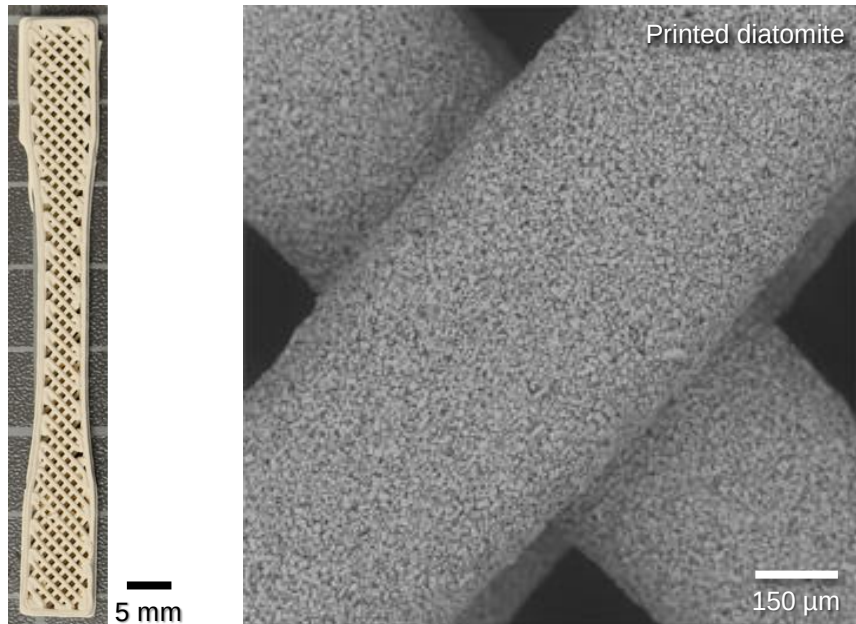
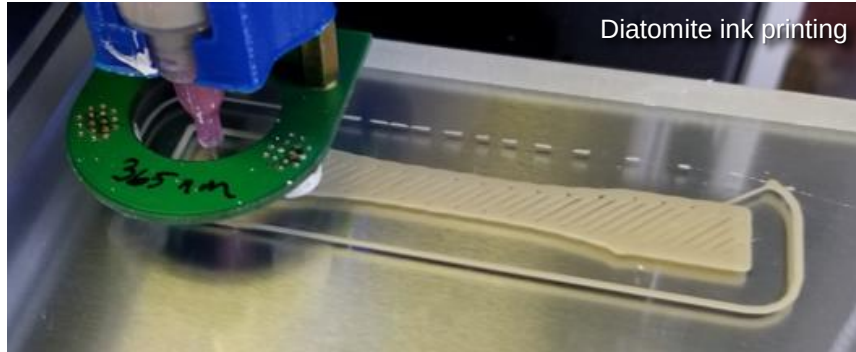


- Navicula trivialis diatoms in sodium alginate gel
- Extruded through nozzle and grown on molded structure
- Diatoms survive and replicate primarily on surface of material

Diatom Bioprinting



Diatomite Printing

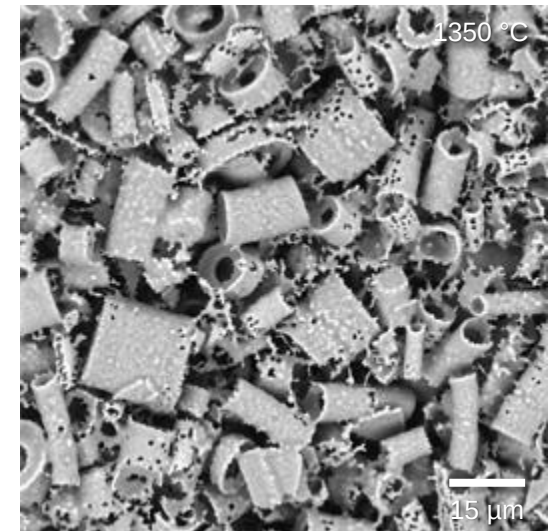
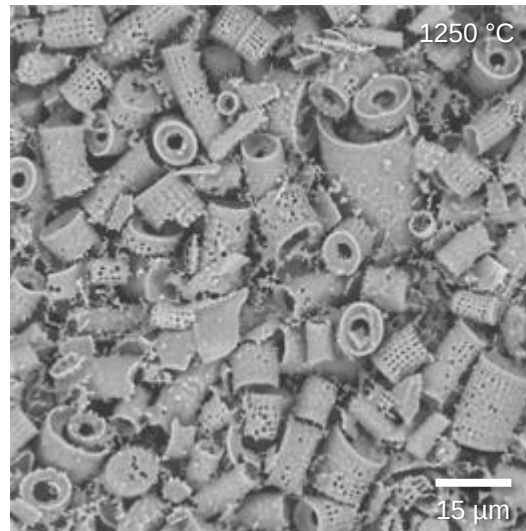


- Issues with grown diatom post-processing
 - Low density
 - Unwanted particles
- Develop printable ink using diatomite to test post-processing procedures
- Diatomite: fossilized diatom frustules
- Previous work does not focus on methods to bond complex structures
- Printable ink: diatomite and sodium alginate composite
- Post-processing to preserve nanostructure and bond diatoms

Diatomite Printing

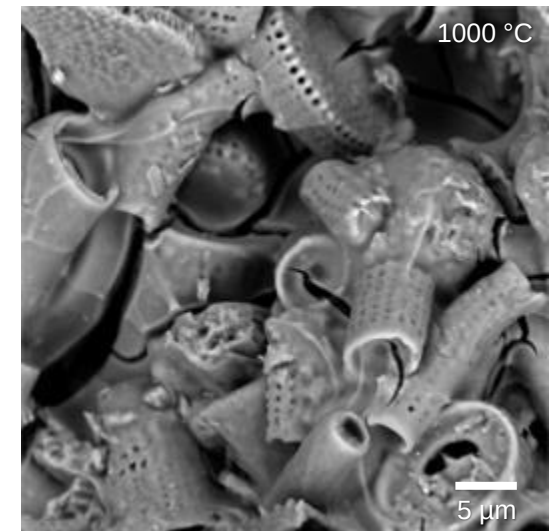
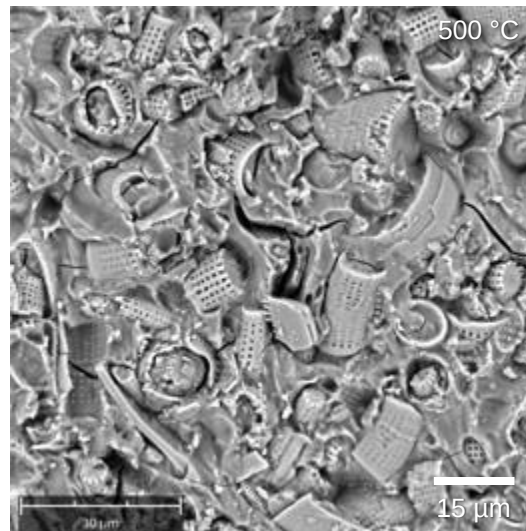
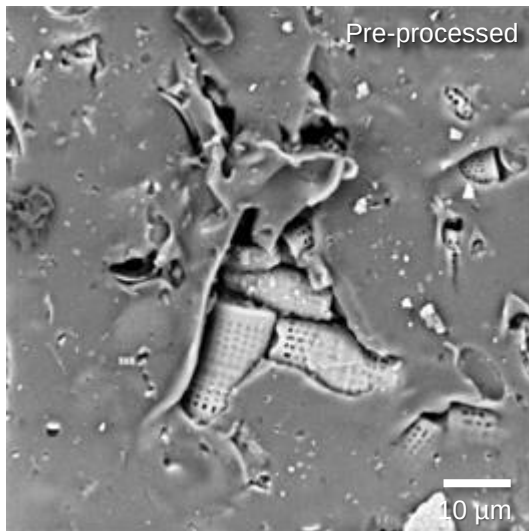
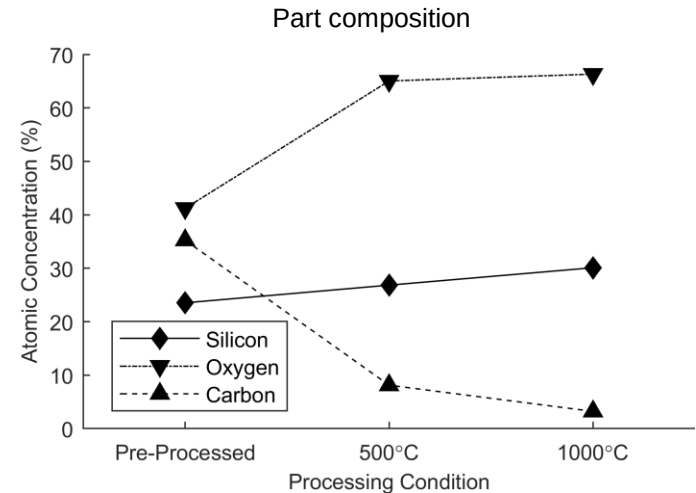


- Post-processing
 - Dried overnight
 - Calcination at 640 °C
 - Bonding at 1000-1350 °C
- Poor bonding between frustules
- Nanostructure destroyed at higher temperatures



Diatomite Printing

- Need additional material to bond diatoms
- Must be printable and silicon based
- Polydimethylsiloxane (PDMS)/diatomite composite
- Calcination converts PDMS to silica
- Higher temperatures improve wetting between diatoms and silica
- Microcracks develop in material



Conclusions and Future Work

- Developed IR heating for high temperature printing to better understand parameter settings influence on mechanical properties.
- Created a modular, machine learning based system that can optimize part quality and is independent of part, machine, or manufacturing method.
- Multifunctional parts were produced by combining additive manufacturing and carbon nanotube yarn.
- Explored use of diatoms in creating hierarchical systems. Incubation and post-processing play important role in growth characteristics and design of the system.
- Developed 3D printable diatomite ink and post-processing technique. Bonding techniques need to be further explored.
- Continue to optimize printing process to achieve larger, more complex hierarchical structures.

Thank You!

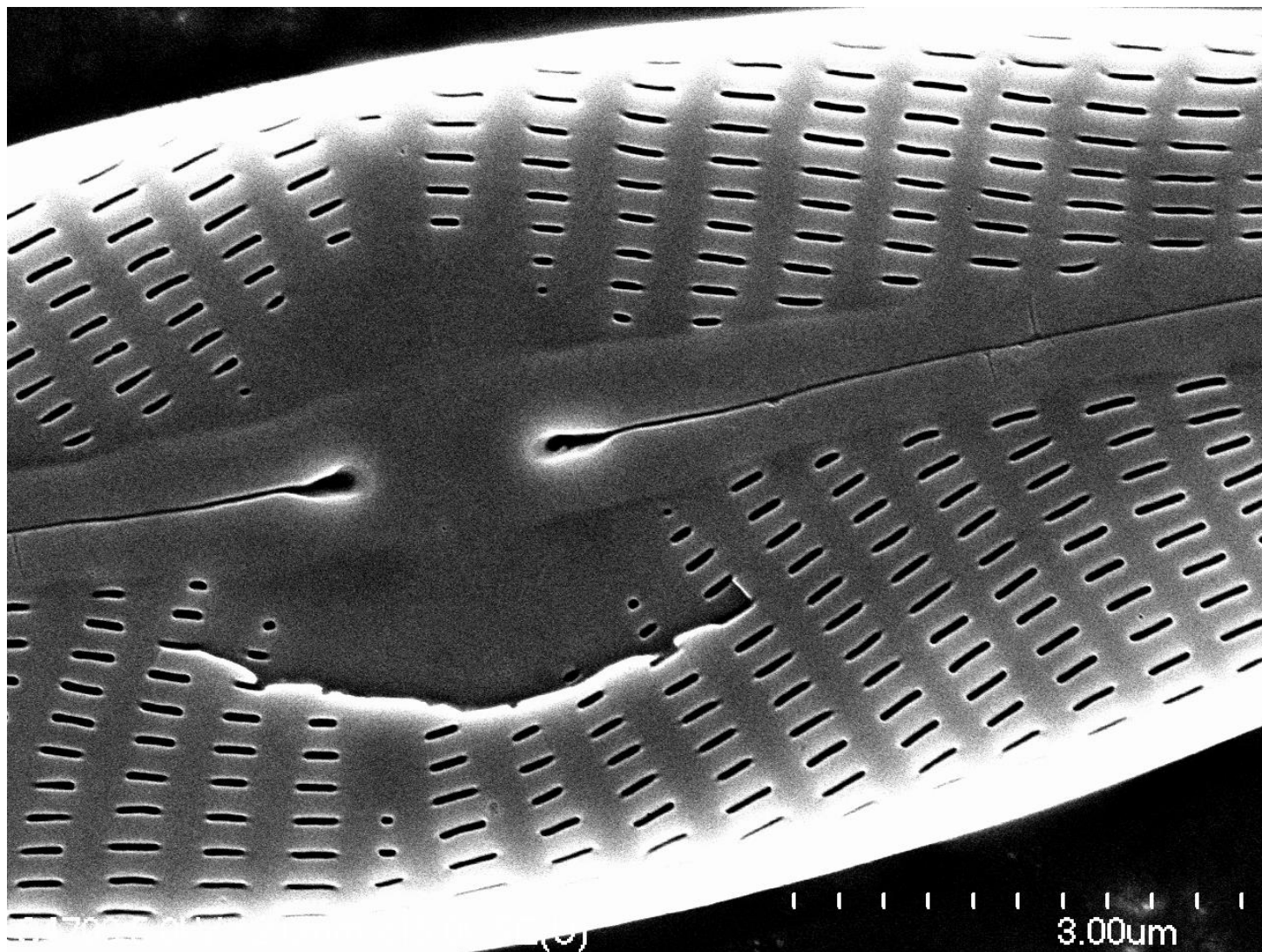


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