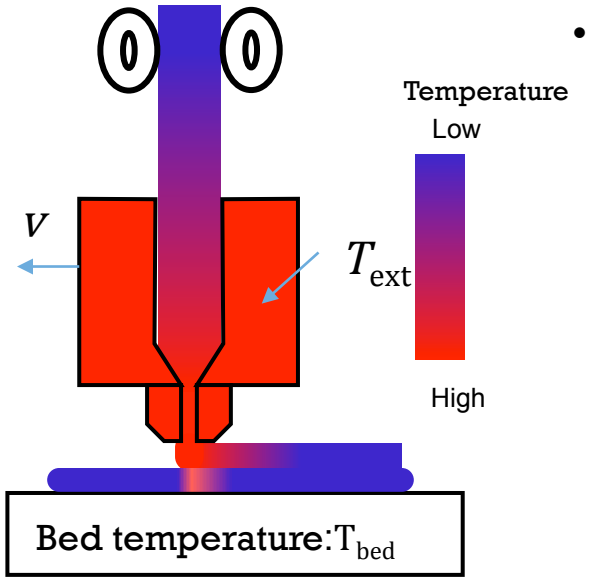
# FDM from a polymer processing perspective: challenges and opportunities

Bryan D. Vogt, Fang Peng, Emily Weinheimer, and Miko Cakmak

Department of Polymer Engineering

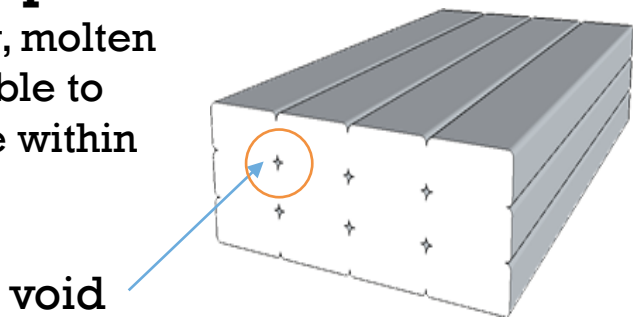
University of Akron

# Challenges of FDM 3D printing




**Incomplete infill results in voids inside printed parts:**

- Due to rapid cooling, molten fiber usually is not able to completely fill space within adjacent fibers

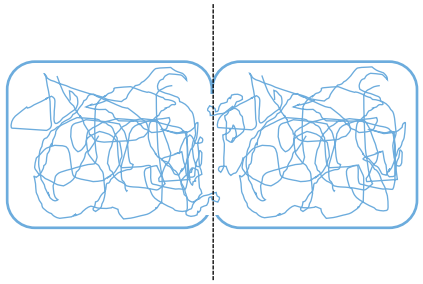



**Fast solidification leads to limited chain diffusion between fibers and layers**

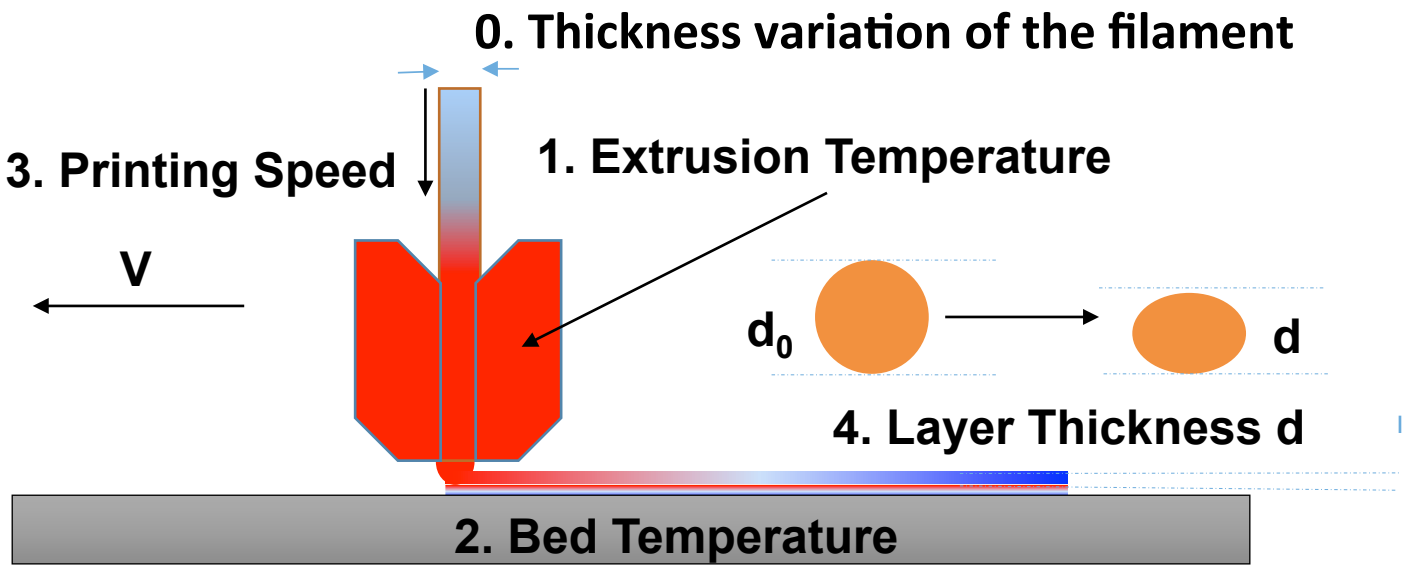
- Significant chain diffusion across fiber interfaces occurs only at high temperature
- Poor mechanical properties at interface due to low level of chain interdiffusion across interface

Process is non isothermal!!

**Poor Mechanical Properties**



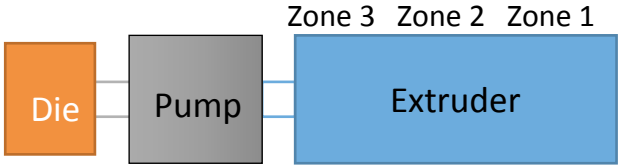
# Challenges for FDM and process control




0. **How does variation in the filament impact the final product?**
1. What is temperature history through the hotend?
2. How is the bed temperature related to the lowest temperature of the part during the print?
3. How does printing speed (and size of object) impact temperature history?
4. Does the thickness of the printed layer (thermal conduction path) impact the temperature history?

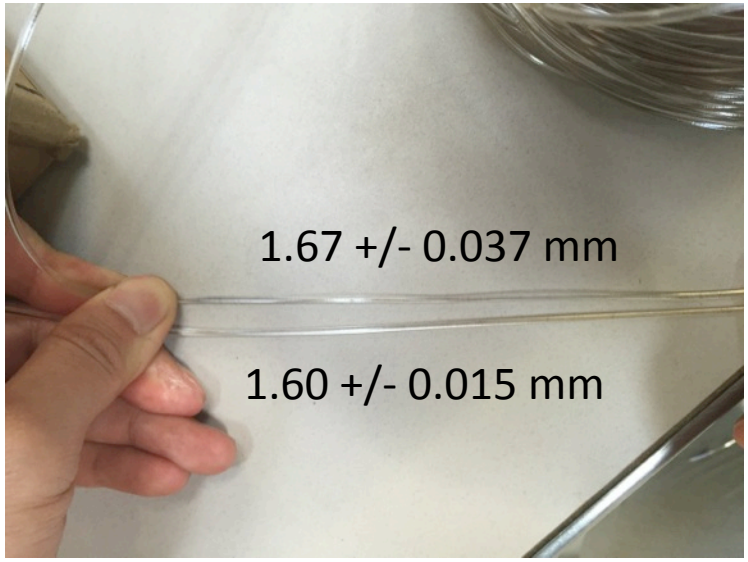
# Filament extrusion and uniformity

Extruder to make ~1.75 mm filament


Switching melt pump impacts filament

Both diameter and variance matter!

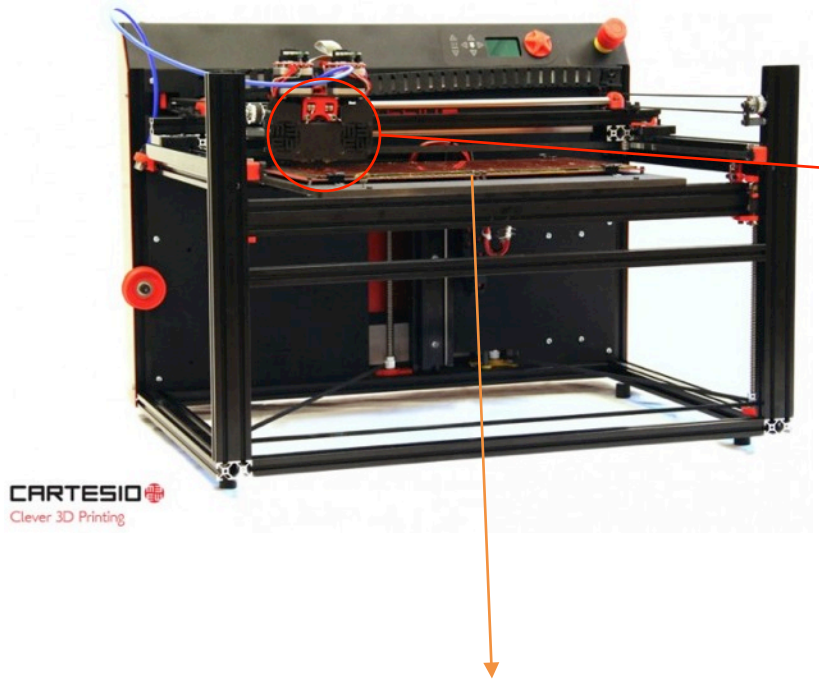



Diameter depends on speed of uptake wheel and melt pump

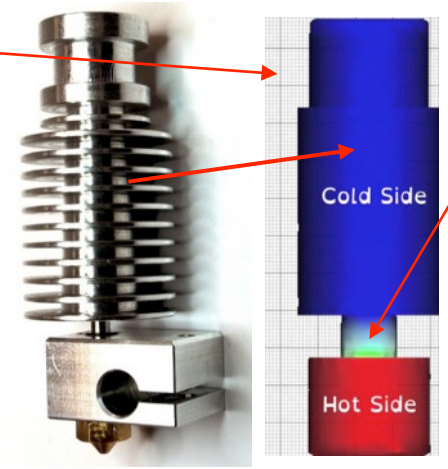
Variance is more problematic than exactly reaching 1.75 mm

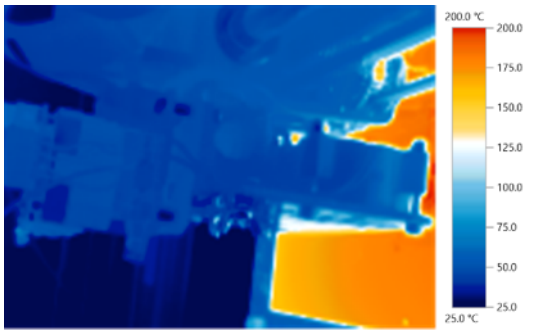
# Customized FDM printer

Cartesio 3D W09




E3D-V6 Hot end: $T_{max}$ = 400 C

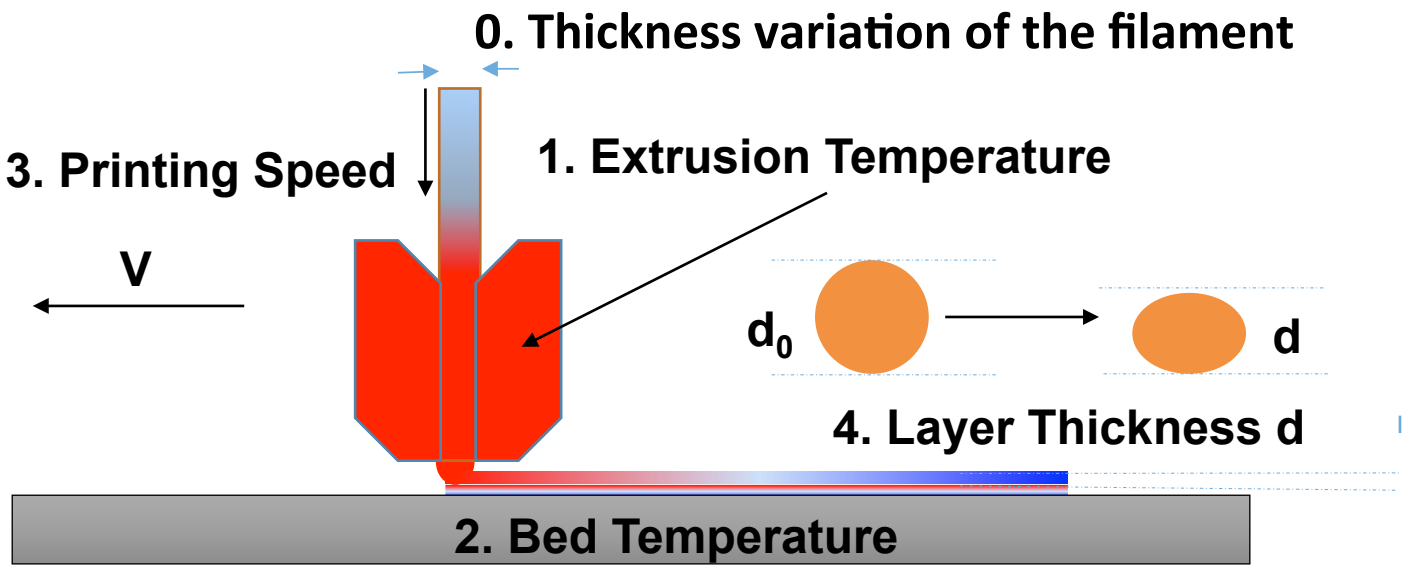



Modified stage to isolated aluminum platform with resistive heaters ($T_{max}$ = 300 C)

Temperature and temperature history control critical to improve control to develop desired properties

# Challenges for FDM and process control

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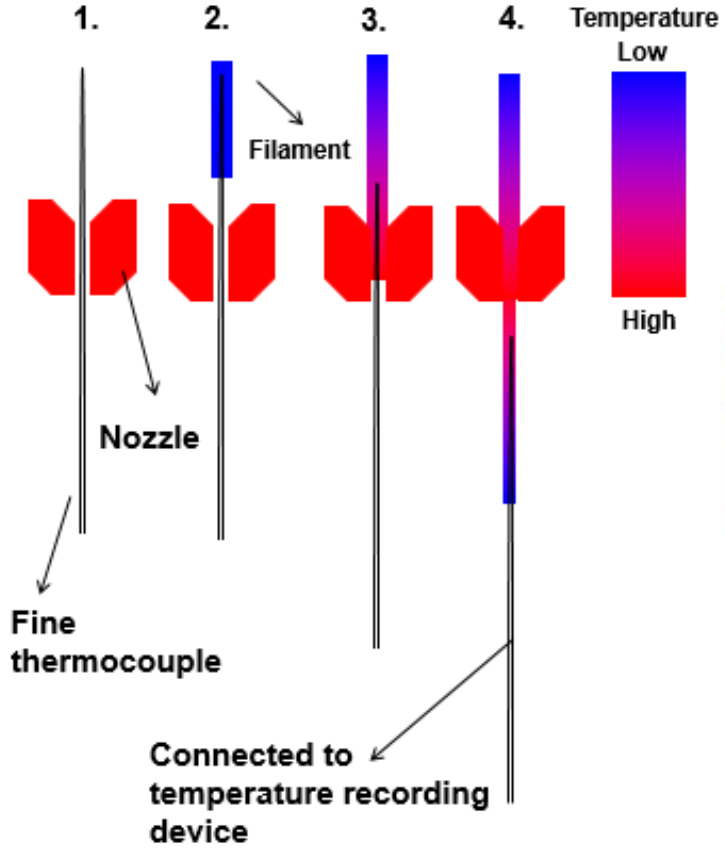
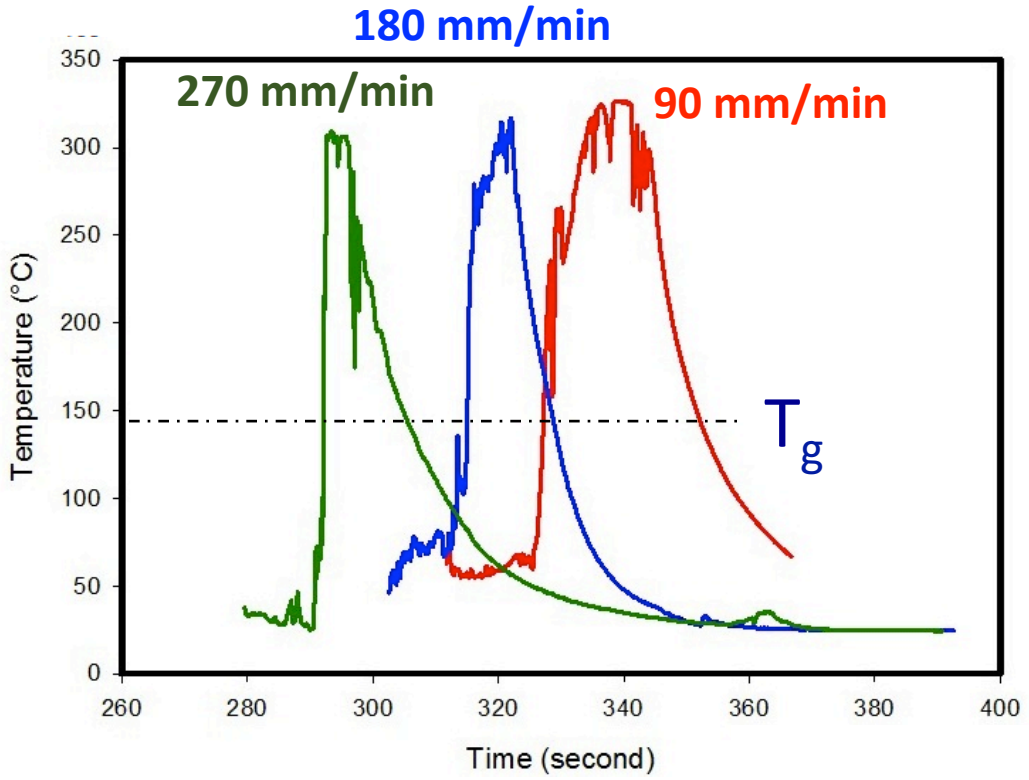
# Temperature profile through extruder head



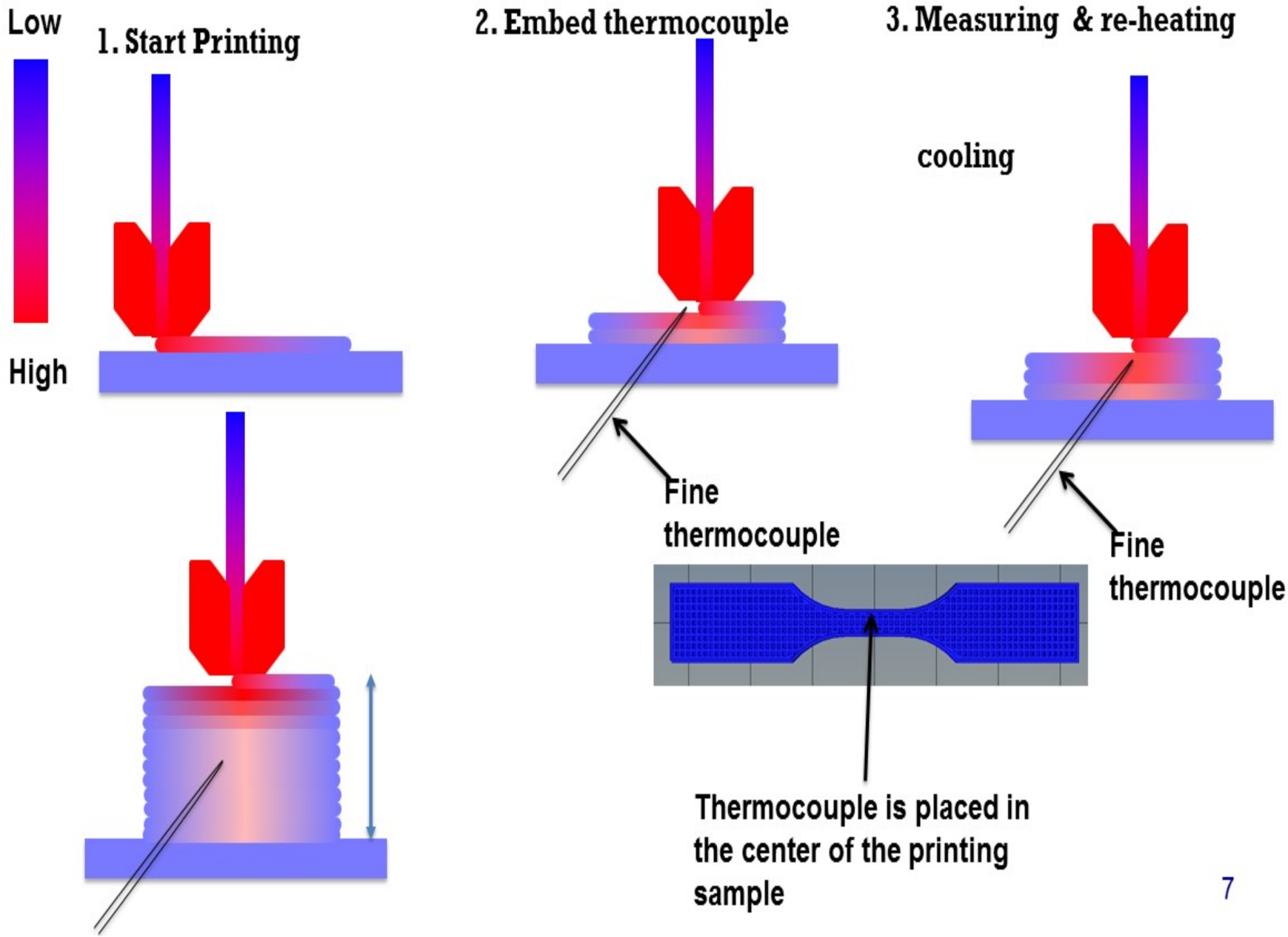




Embed thermocouple in filament through the extruder

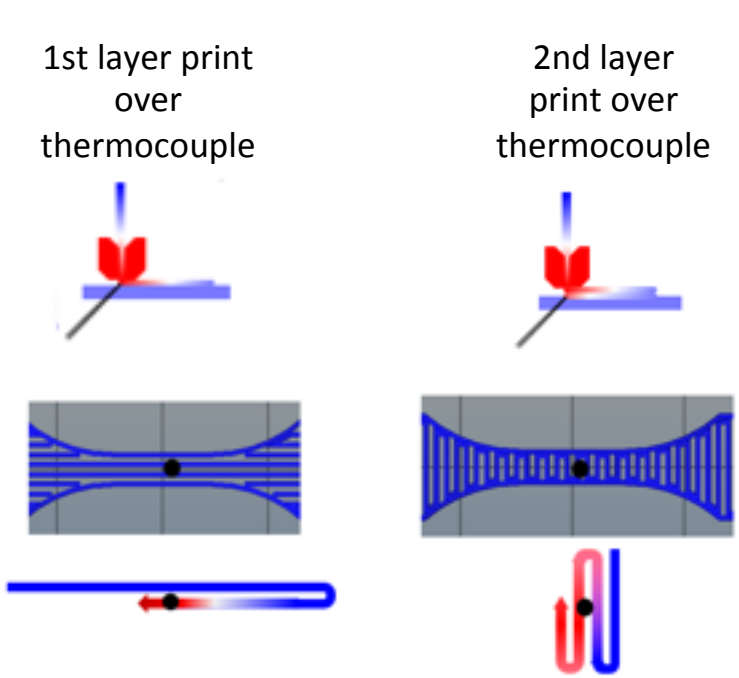
What is the extruder variation for identical FDM systems?
What about system differences?

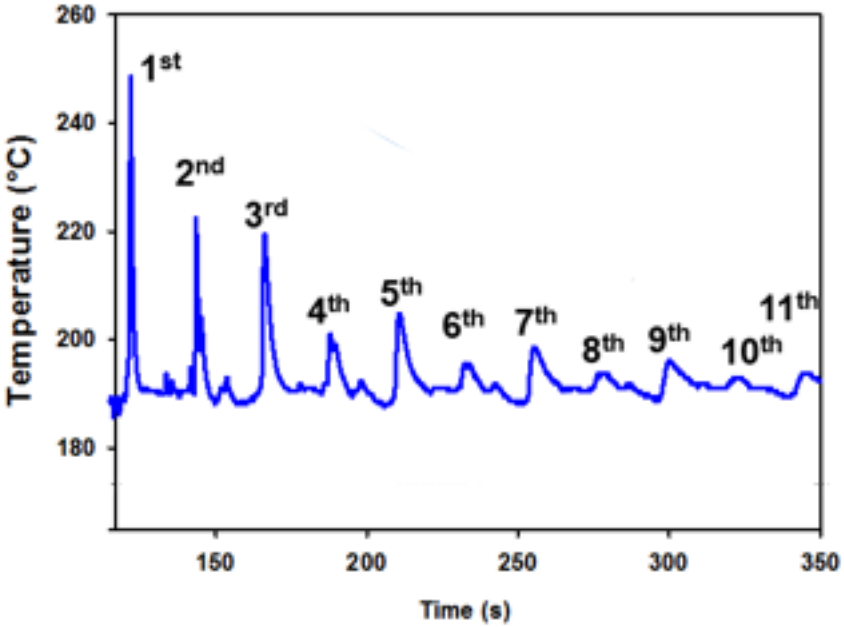
Total time in the melt out of the extruder is <1 min
Potential for processing history in the filament manufacture to be transferred to final part

# 3D printing is extremely non-isothermal



# Temporal and spatial complex temperature history of part



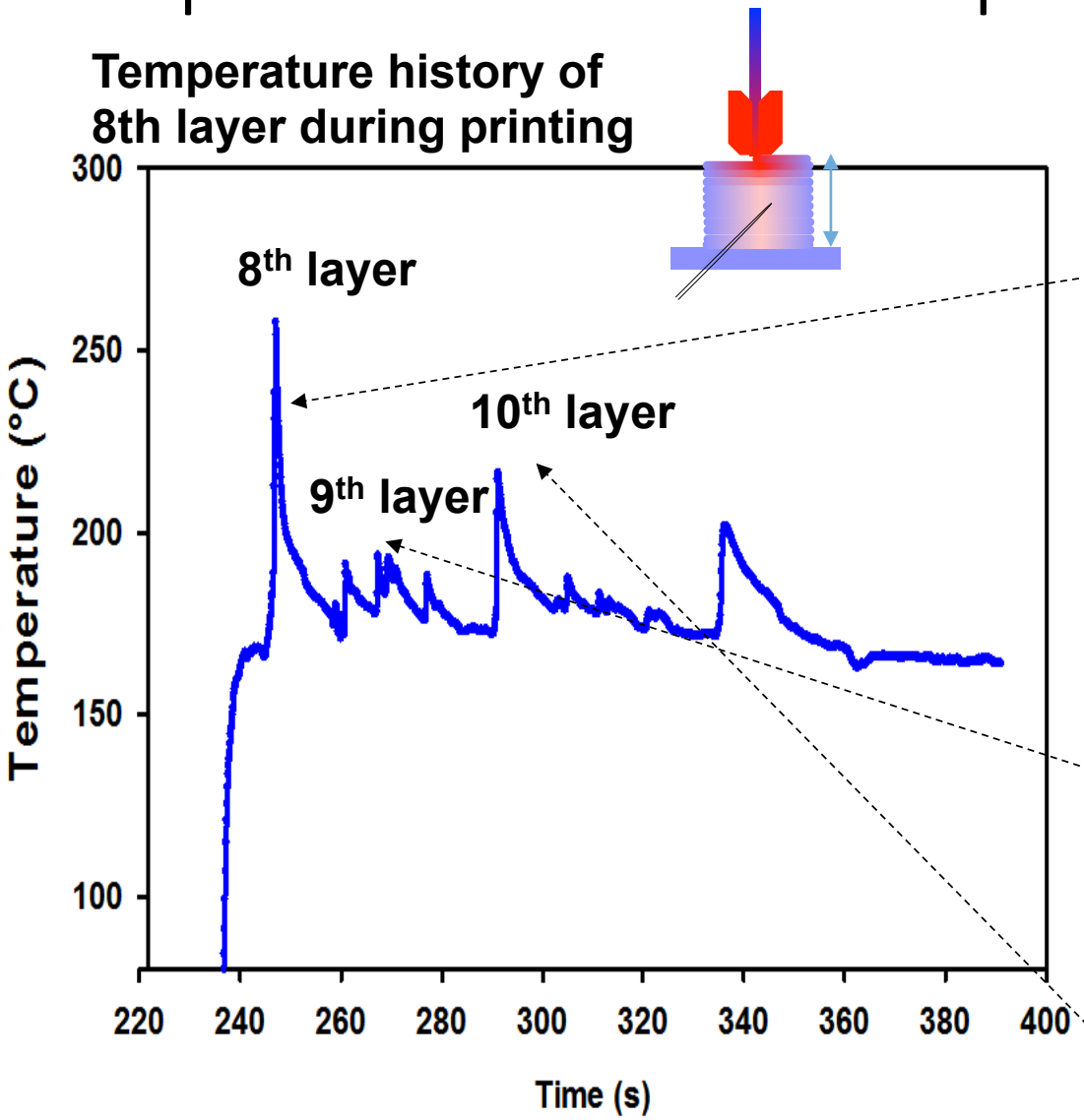

Local temperature history is very complex

Exact location of the measurement will impact the measured profile

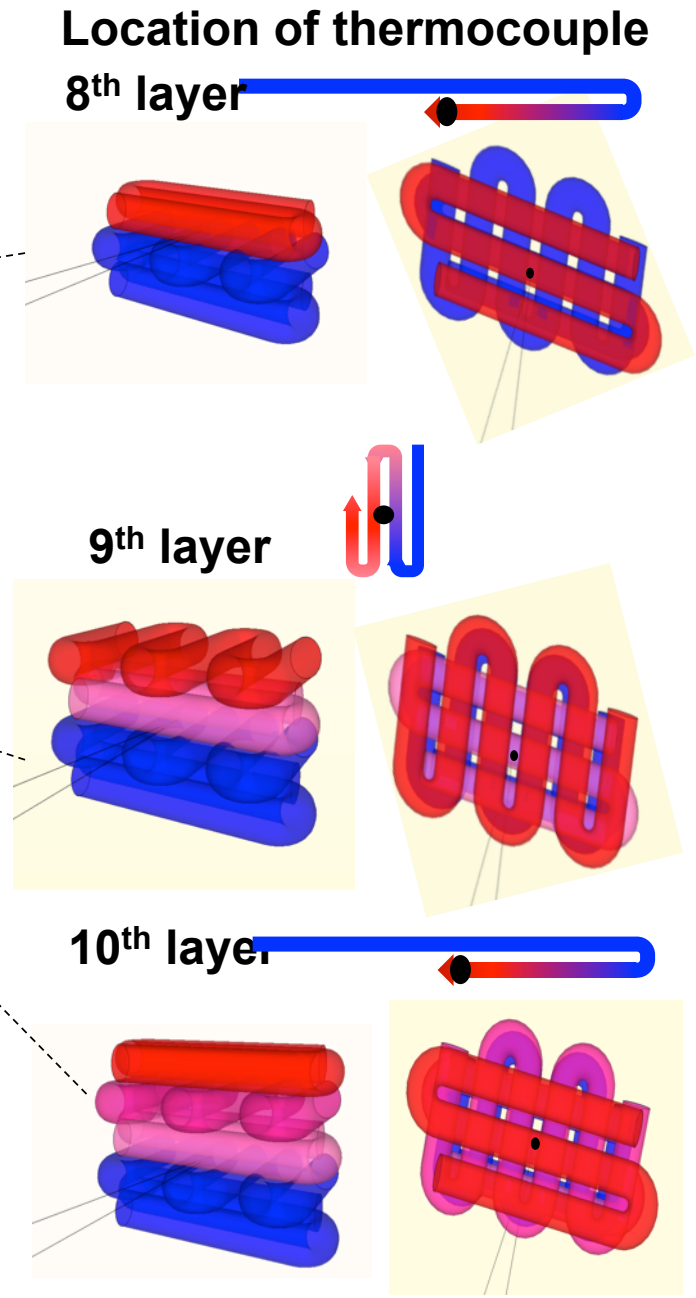
Need for simulations that provide the temperature history distribution

The size of the part matters for the history

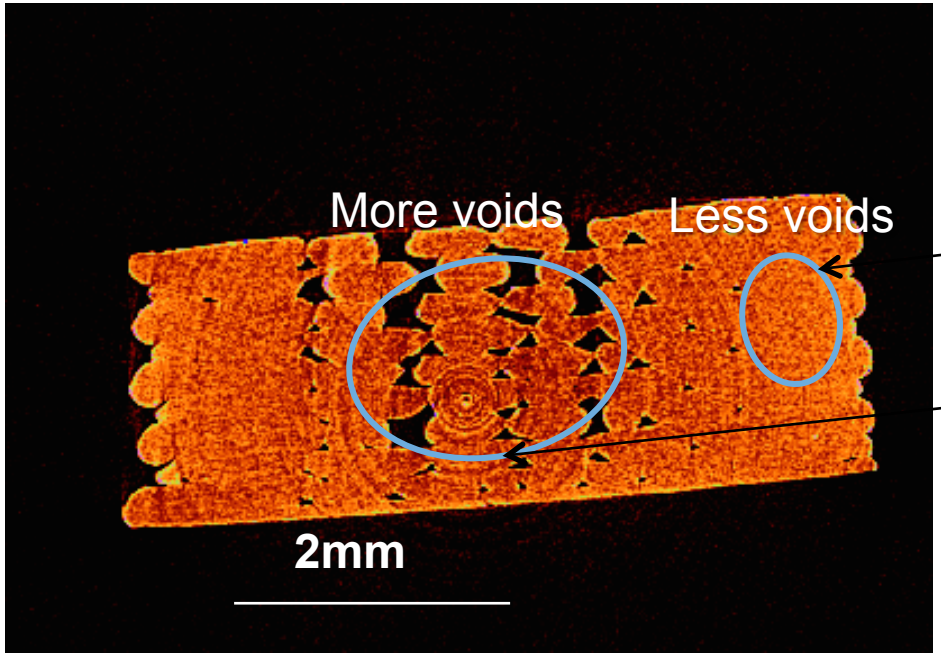
# Temperature in the 3D printing process

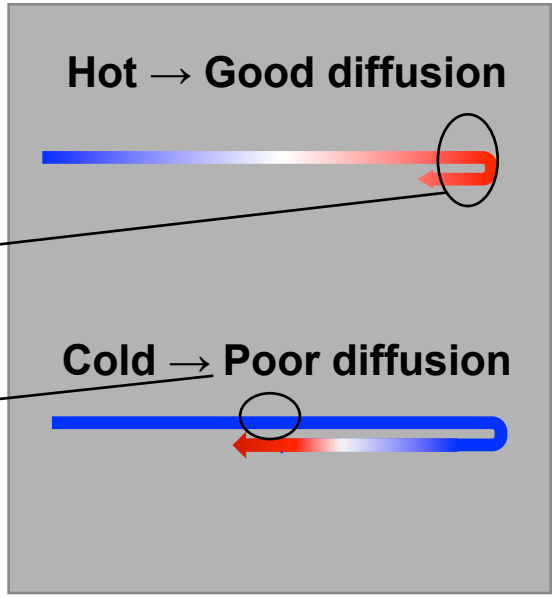



Printing temperature : 300 °C
Printing speed: 40mm/s
Bed Temperature: 185 °C

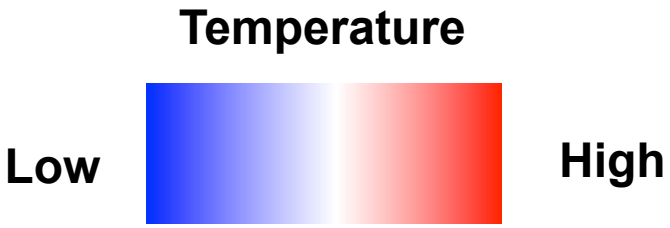


# Role of temperature history on defect distribution



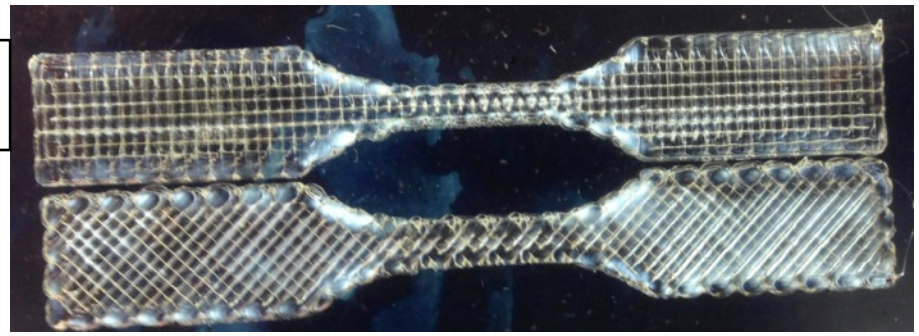

Process temperature history critical to properties of part



# Part failure - remnants of initial filament

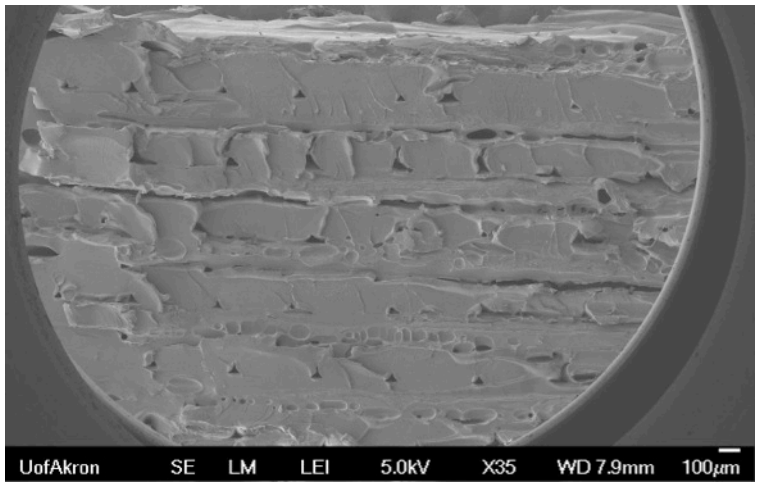
0°-90°

±45°

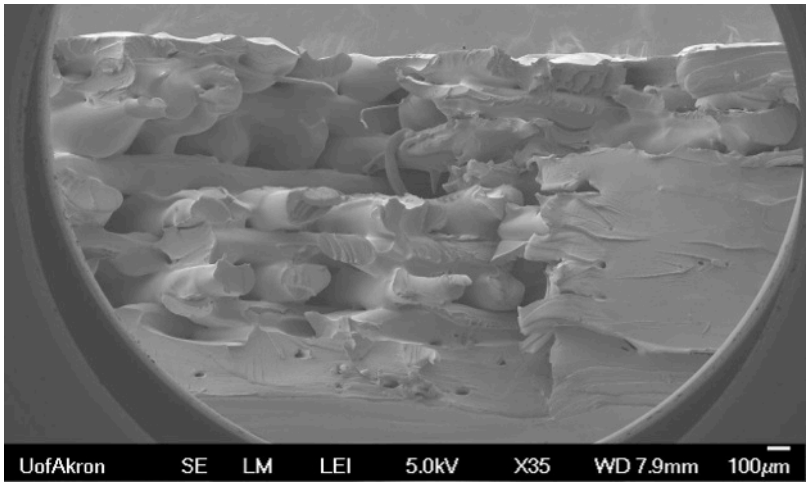


Poorly selected print conditions to maximize voids

**Printing pattern: 0°-90°**

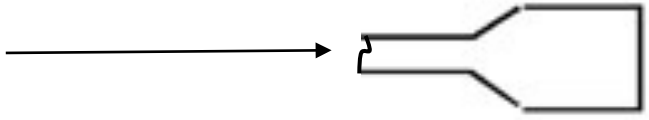



**Printing pattern: -45°-+45°**



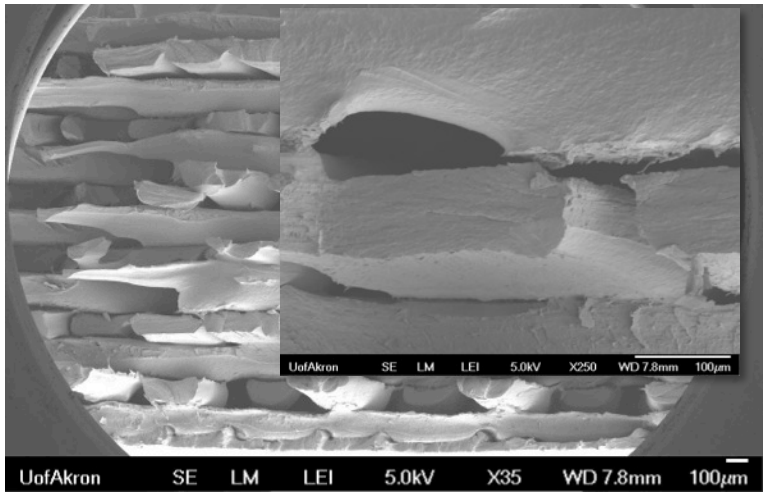

(polycarbonate)

**SEM images of fracture surface of FDM printed tensile bar**

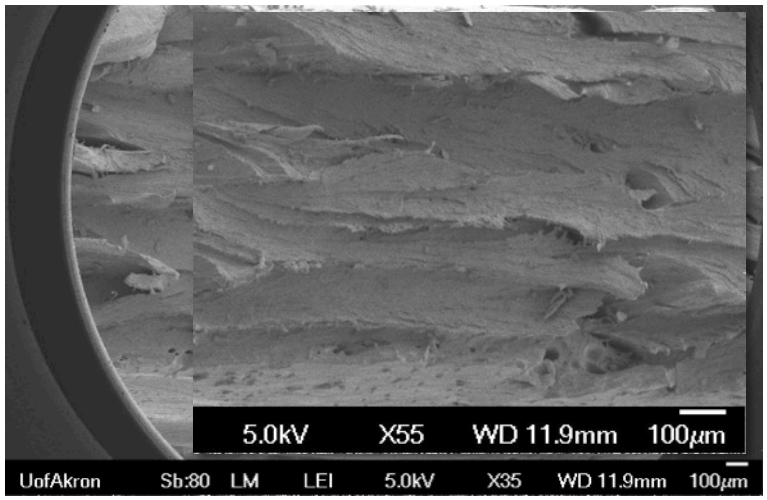


# Role of Extrusion temperature

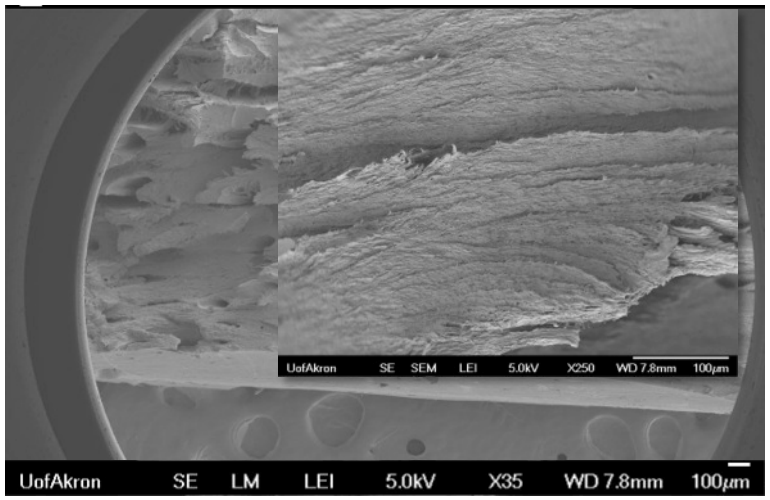
**260 °C**




**285 °C**




**310 °C**

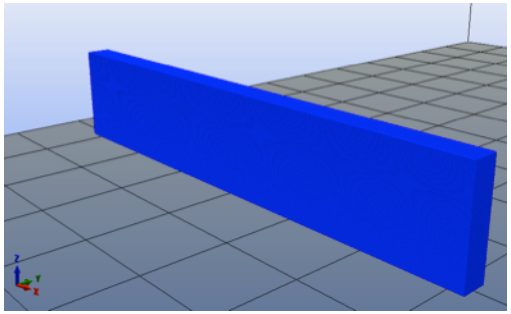


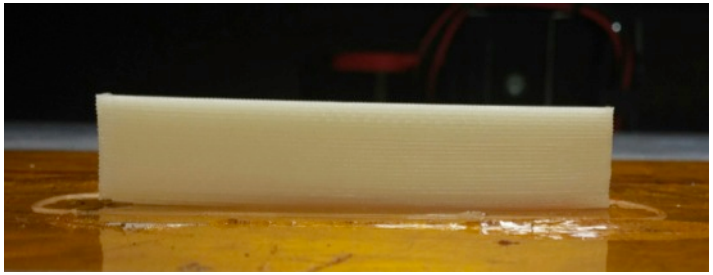

Polymer: PC/ABS blend
Layer thickness: 0.15 mm
Printing pattern: 45 °

Extrusion temperature determines interdiffusion

# Composite-like failure in PC/ABS blend

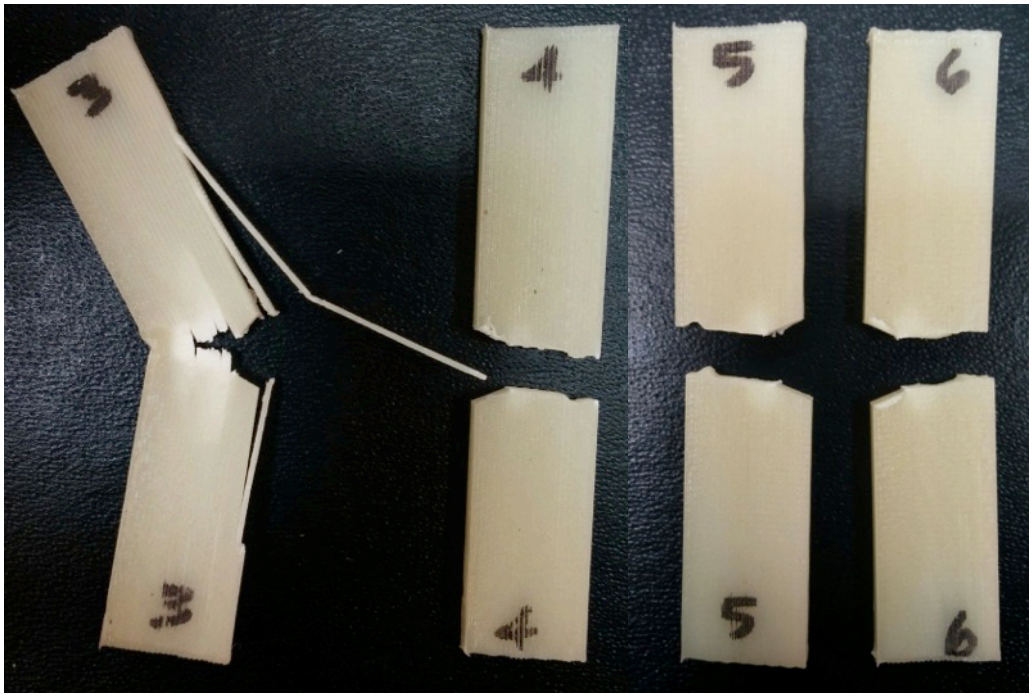
Edge-on printing of impact bar





0-90 orientation

45-45 orientation




| Notch position: | top | bottom | top | bottom |
|---|---|---|---|---|
| Impact strength (ft-lb/in) | 15.1 (0.2) | 2.8 (0.1) | 1.6 (0.5) | 2.2 (0.5) |

N = 4

Order of magnitude difference in the impact strength depending on **print direction** and **notch location** (highly anisotropic materials)

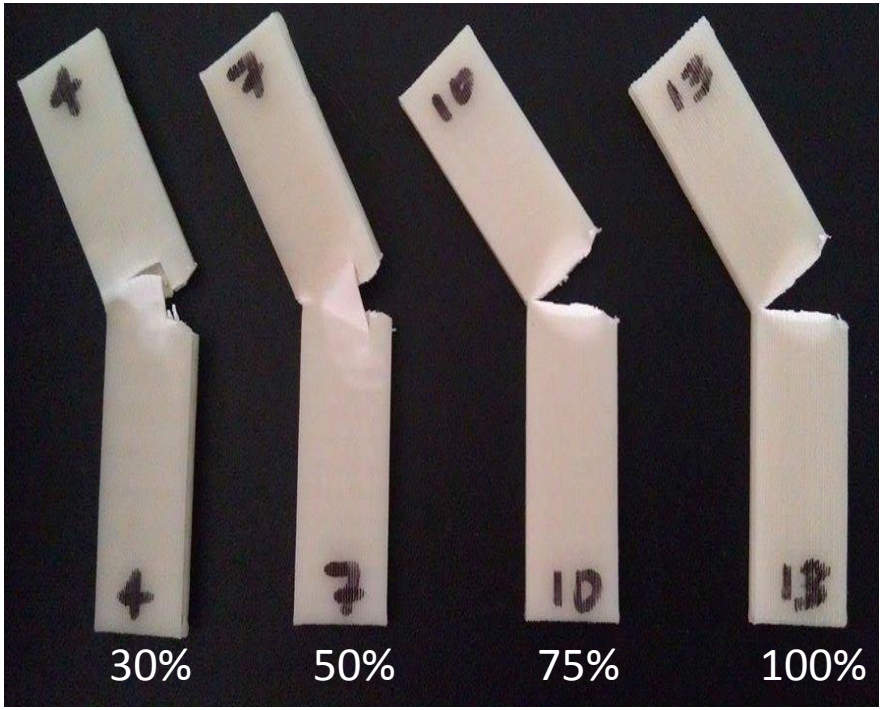
# Exploited 3D printing – cellular solids

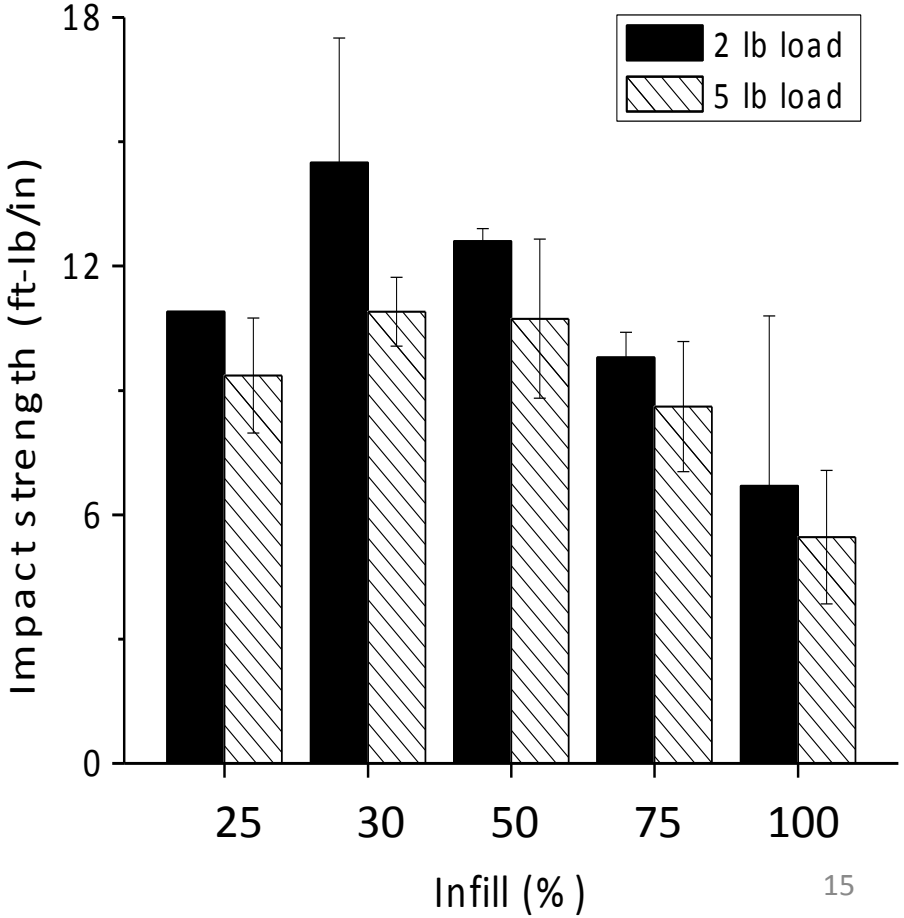
Sample infill

25%

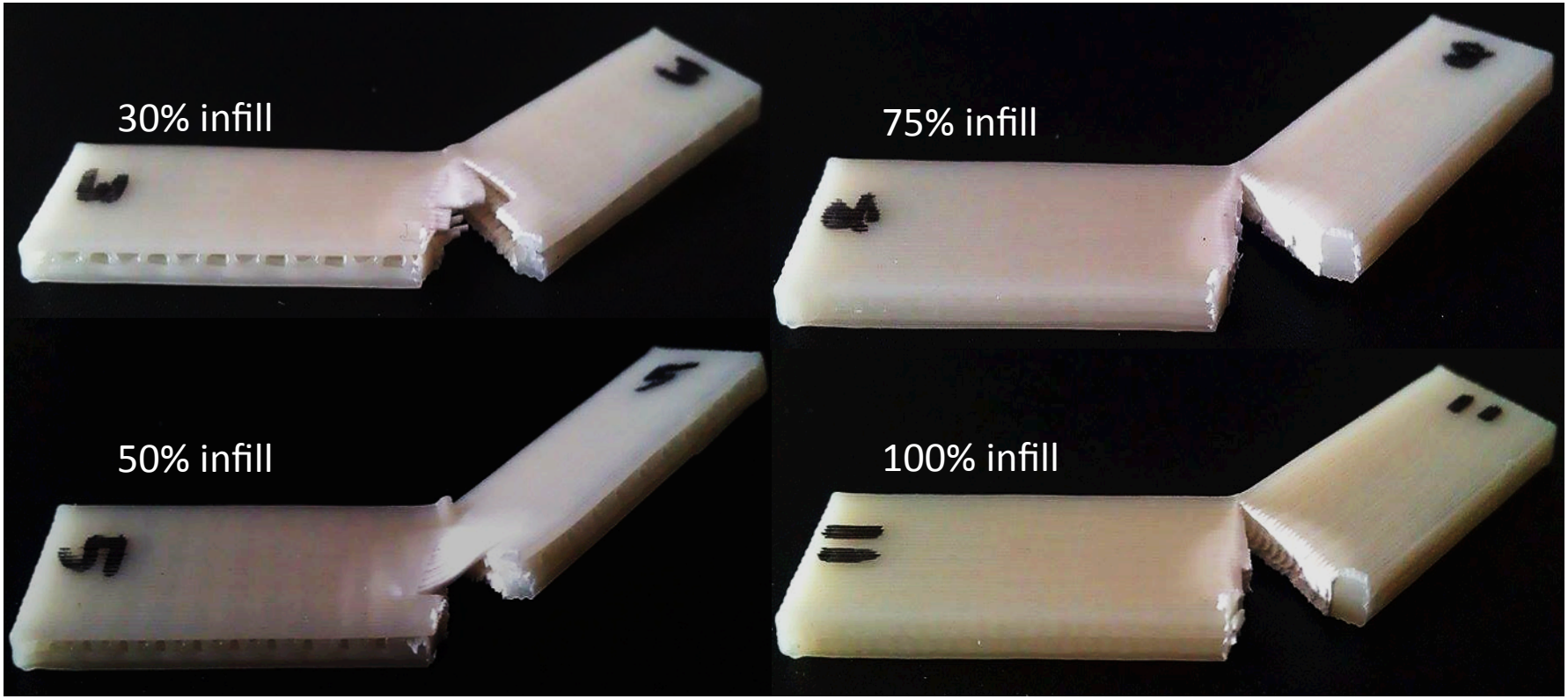
100%

Partial break occurs upon 2 lb load



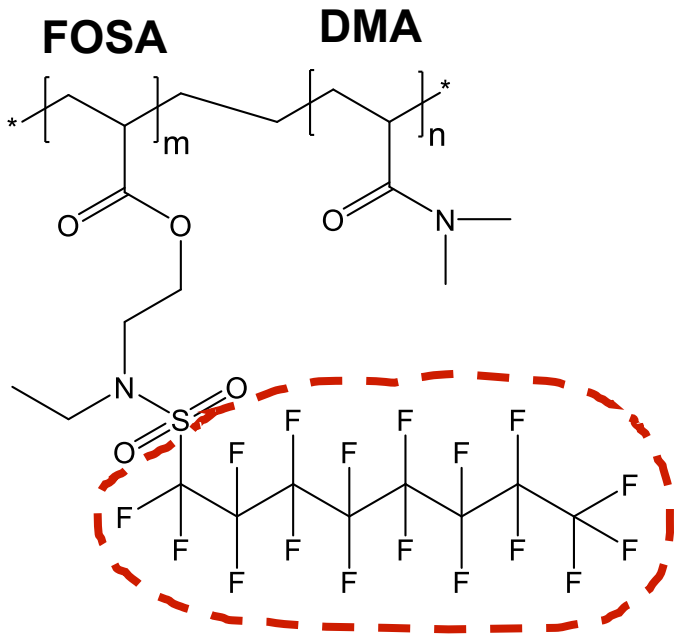
# Failure of cellular print



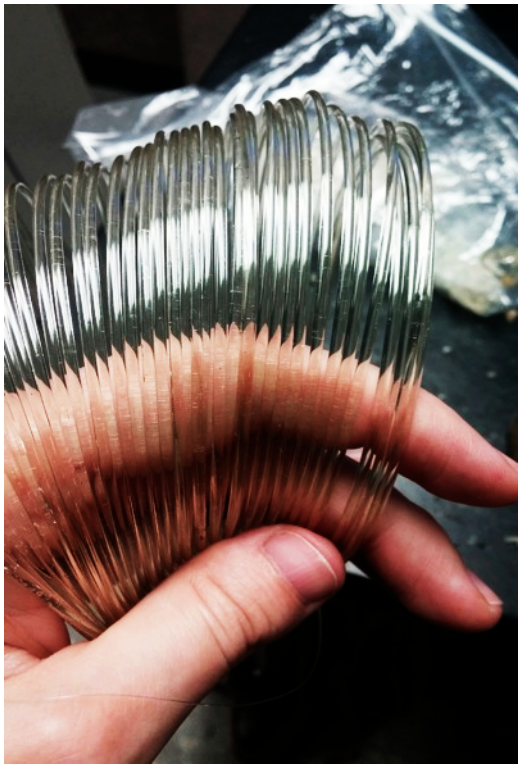

50% infill does not completely break under a 2 lb load.

# Responsive polymers – thermoplastic hydrogels

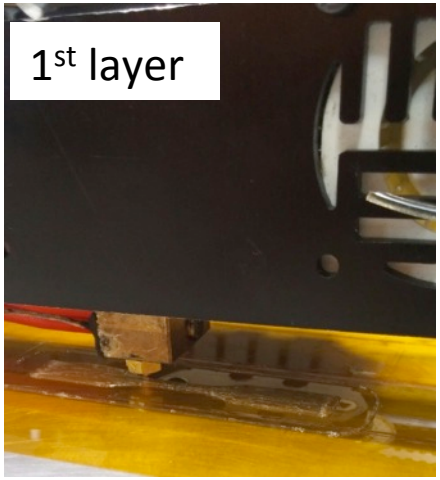
Synthesize copolymer

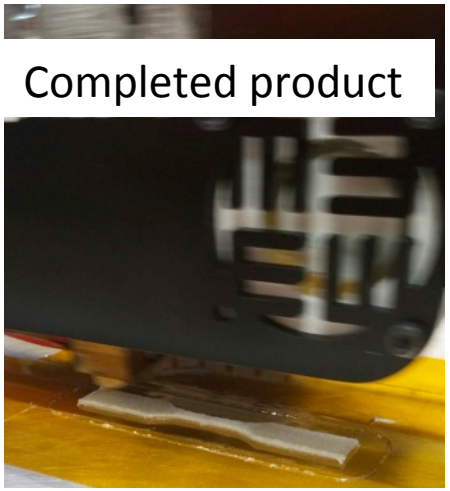



Extrude filaments



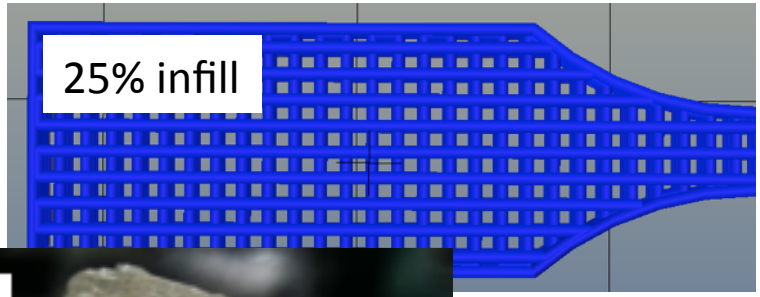
3D print



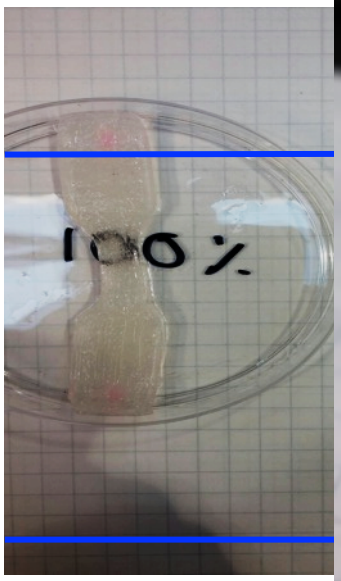



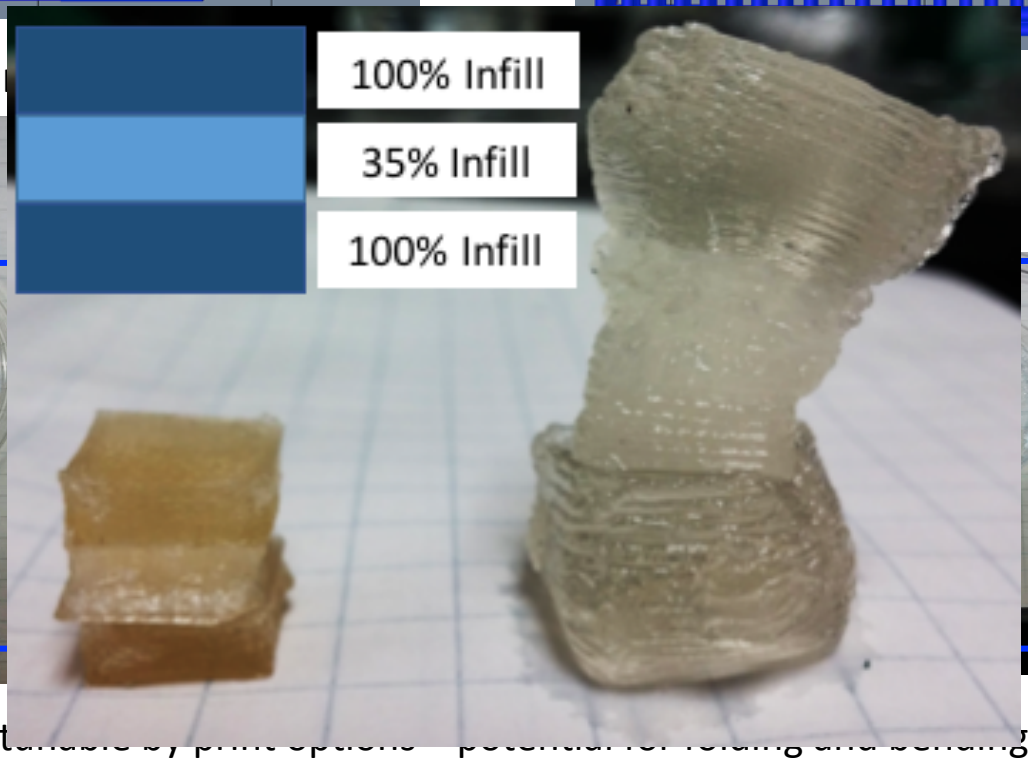

Dry “Hydrogel”

# Using print processing to control response


Comparison of hydr



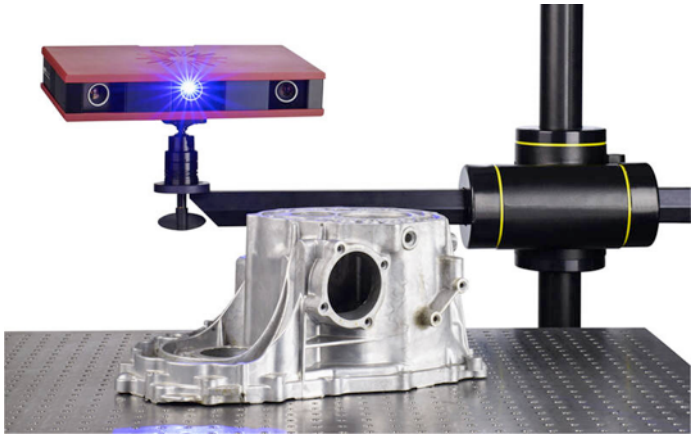

Swelling of sample is t[illegible] on swelling

# Summary and unmet challenges

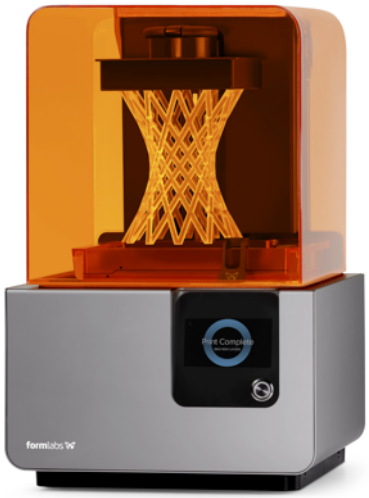
- Complex temperature history for FDM printed parts
  - Need integration of modeling and experiments
- Integration of thermal history and expected properties?
  - Anisotropic properties
  - Design of print based on expected stress loads?
- Wealth of new possibilities to explore with FDM
  - New materials (filament extrusion and uniformity)
  - Tunable failure by print conditions?
- Improved process knowledge is key to future success

# New 3D printing laboratory at Akron

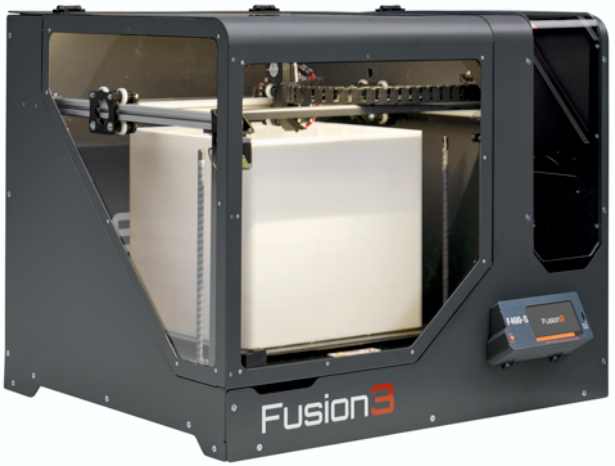
ATOS Core | Blue Light 3D Scanner



Formlab (stereo)

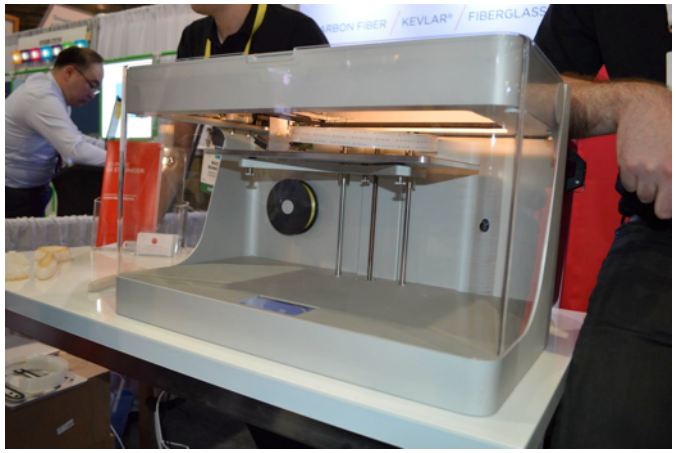


Fusion 3 (FDM)




uPrint SE 3D printer

Markfordrged (FDM)



Objet30 Pro (jet)