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Exploring the functional performance of a commercial high-temperature photopolymer resin for vat photopolymerized injection molding tools

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2025 Solid Freeform Fabrication Symposium

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Outline

Introduction
- Vat photopolymerization (VPP) additive manufacturing (AM)
- Injection molding

Materials & Methods
- VPP mold fabrication
- Injection molding using VPP molds

Results & Discussion
- Resin characterization
- VPP-printed resin characterization
- VPP-printed mold characterization
- Injection molded specimens

Summary & Future Work

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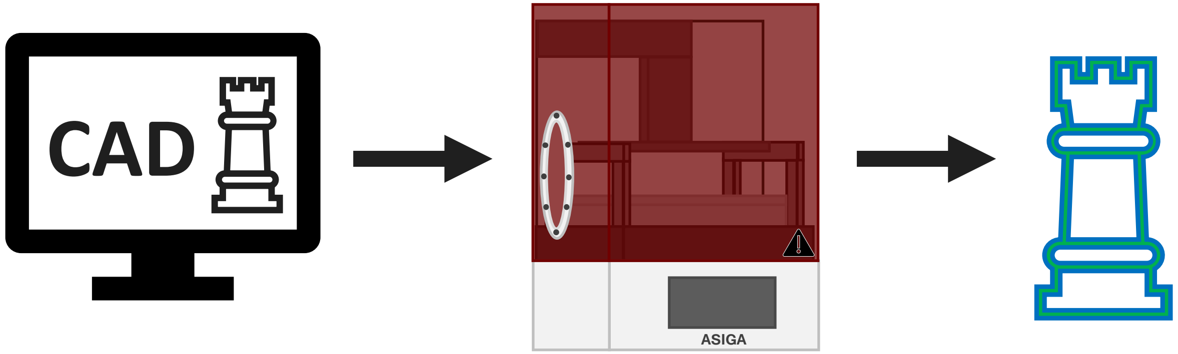
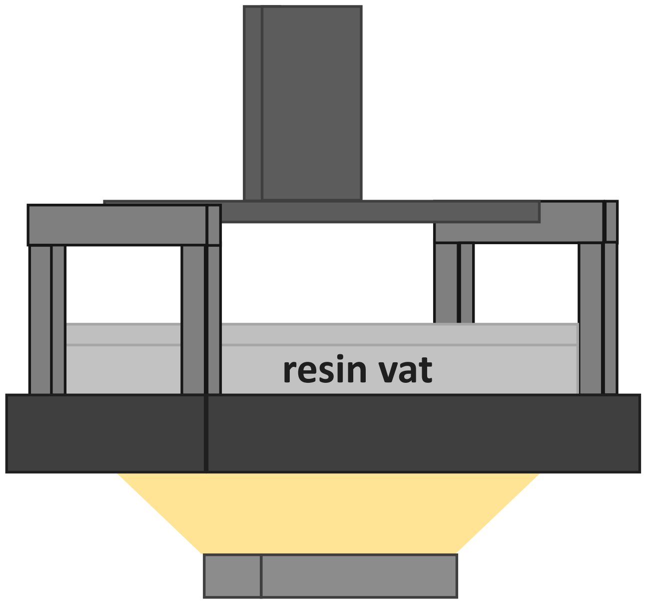
Vat photopolymerization (VPP) additive manufacturing (AM)

- Selective photopolymerization of a liquid photocurable resin using ultraviolet (UV) or visible light in discrete layers
- Photocurable resins are typically a mixture of monomer(s), oligomer(s), photoinitator(s), and additive(s), when applicable
- Recent advances in high-performance resins have made VPP increasingly viable for functional tooling applications





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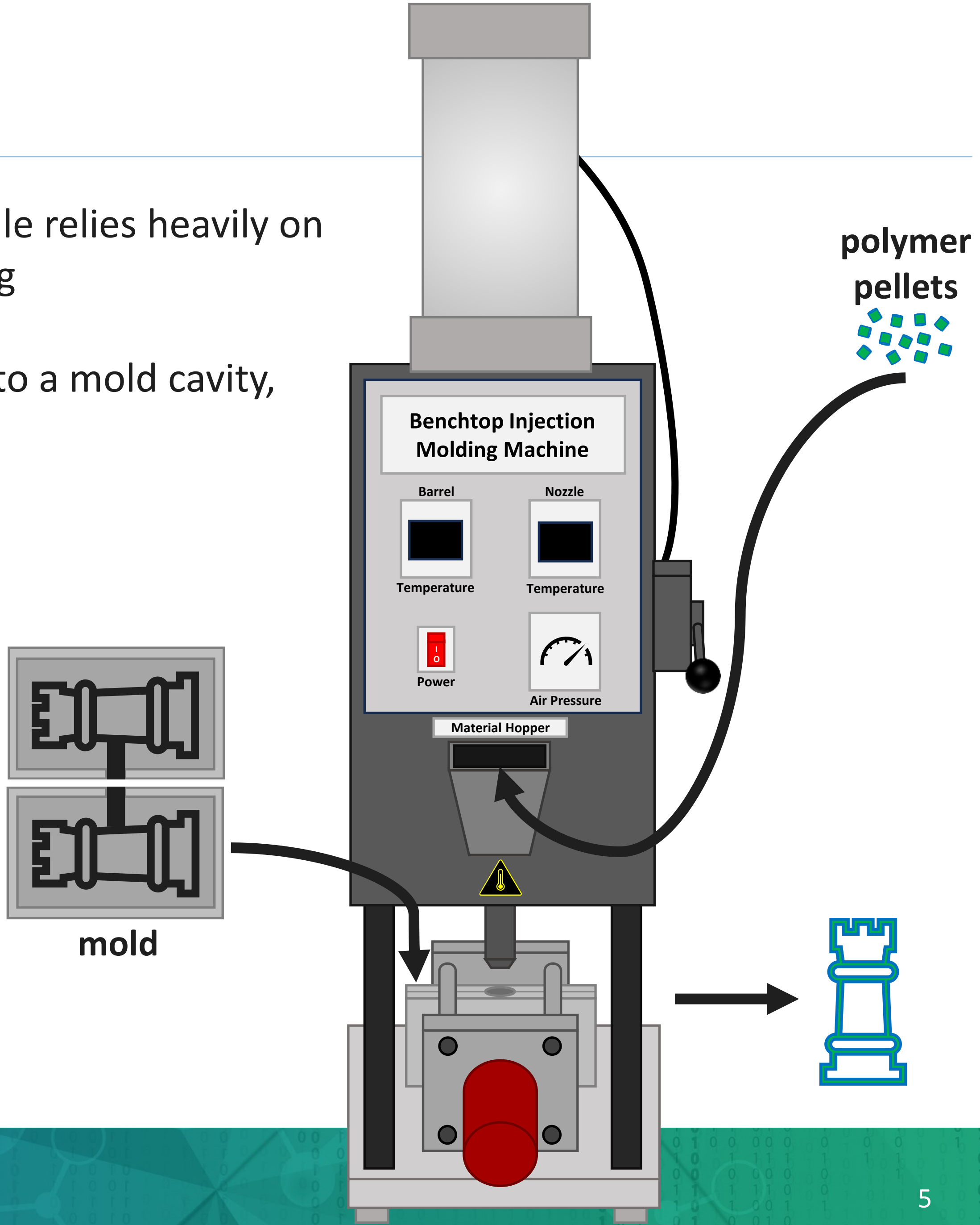
Becerra-Borges, Y. E. et al. Rapid Prototyping Journal 31, 200-217 (2025).
Zhang, F. et al. Additive Manufacturing 48, 102423 (2021).

Injection molding

- Traditional production of thermoplastic polymer components at scale relies heavily on formative manufacturing (FM) techniques, such as injection molding
- A high-volume FM process in which a molten polymer is injected into a mold cavity, where it cools and solidifies into the desired geometry
- Traditionally uses metal tooling for the manufacturing of parts with high repeatability and excellent surface finish
- Metal molds are **costly** and **time-intensive** to produce, limiting their practicality for low-volume or iterative product development

VPP AM is well-known to fabricate high-resolution parts with smooth surface finishes and excellent dimensional accuracy, making VPP an compelling candidate for injection molding tools



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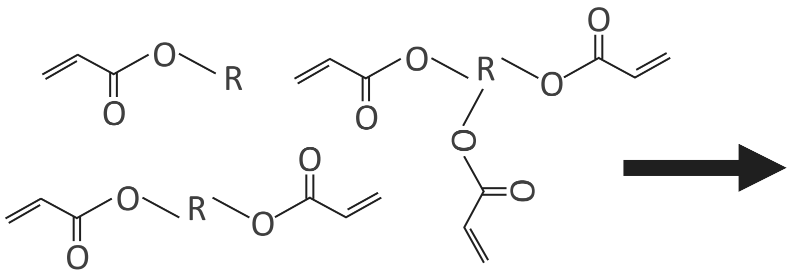
VPP mold fabrication

FormLabs High Temp resin (v2)

- Commercial off-the-shelf (COTS) acrylate-based photocurable resin

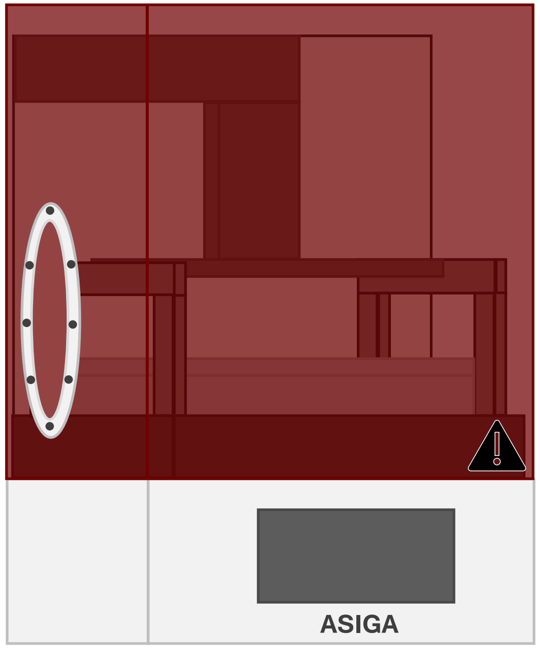
Asiga Max UV385 printer

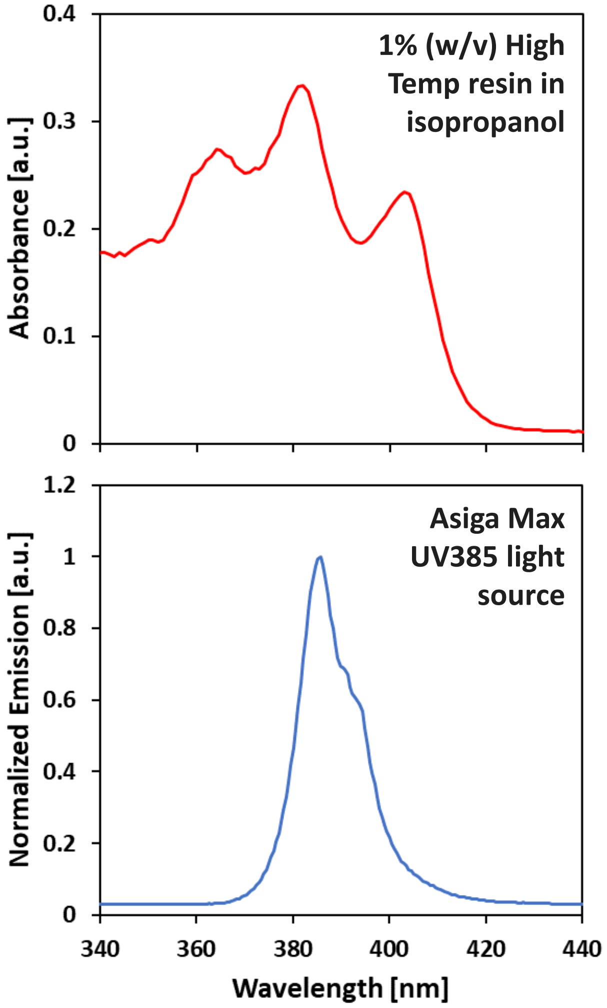
- COTS VPP printer equipped with a 385 nm high-power UV-LED light source and heated resin tank held at 30°C



FormLabs High Temp resin (v2)

acrylate, diacrylate, and triacrylate monomers

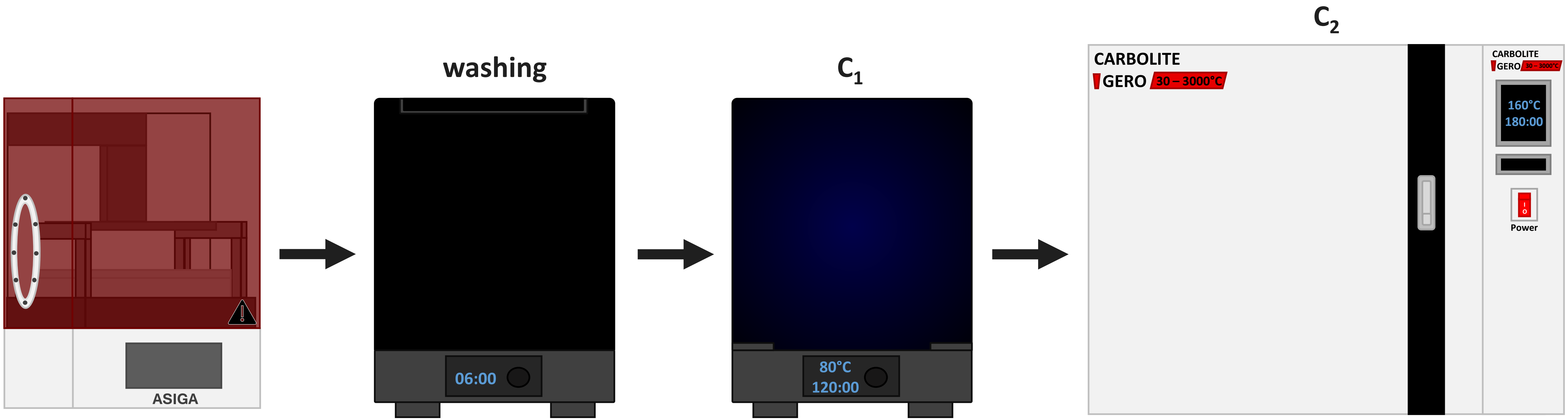




VPP mold fabrication

Post-Print Processing

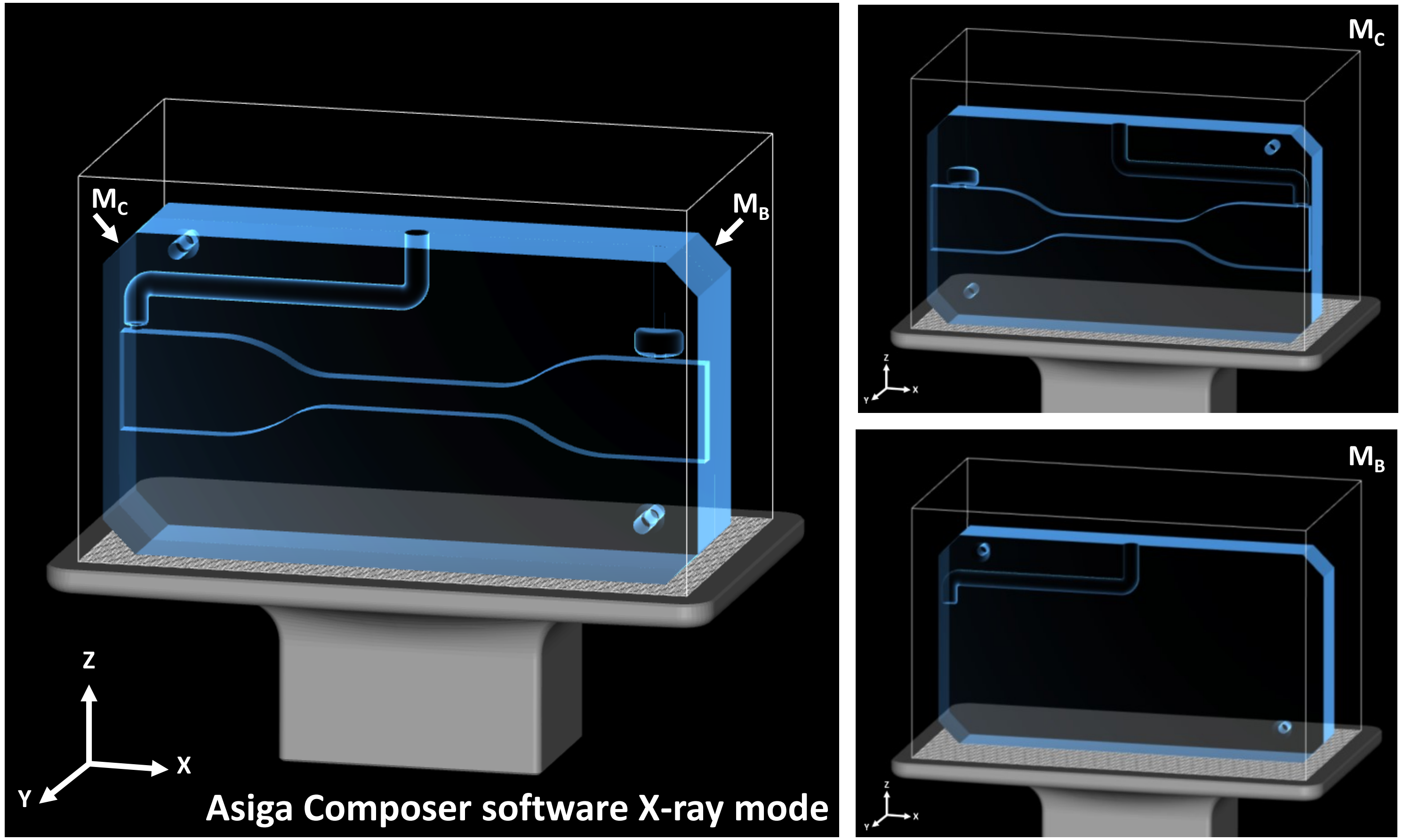
- Washing – Form Wash; 6 min in isopropanol
- Post-cure 1 (C1) – Form Cure; 120 min at 80°C
- Post-cure 2 (C2) – Carbolite GERO LHT Oven; 180 min at 160 °C
- Resurfacing via CNC milling machine



VPP mold fabrication

STLs designed in Creo

ASTM D638 Type IV tensile bar specimen mold



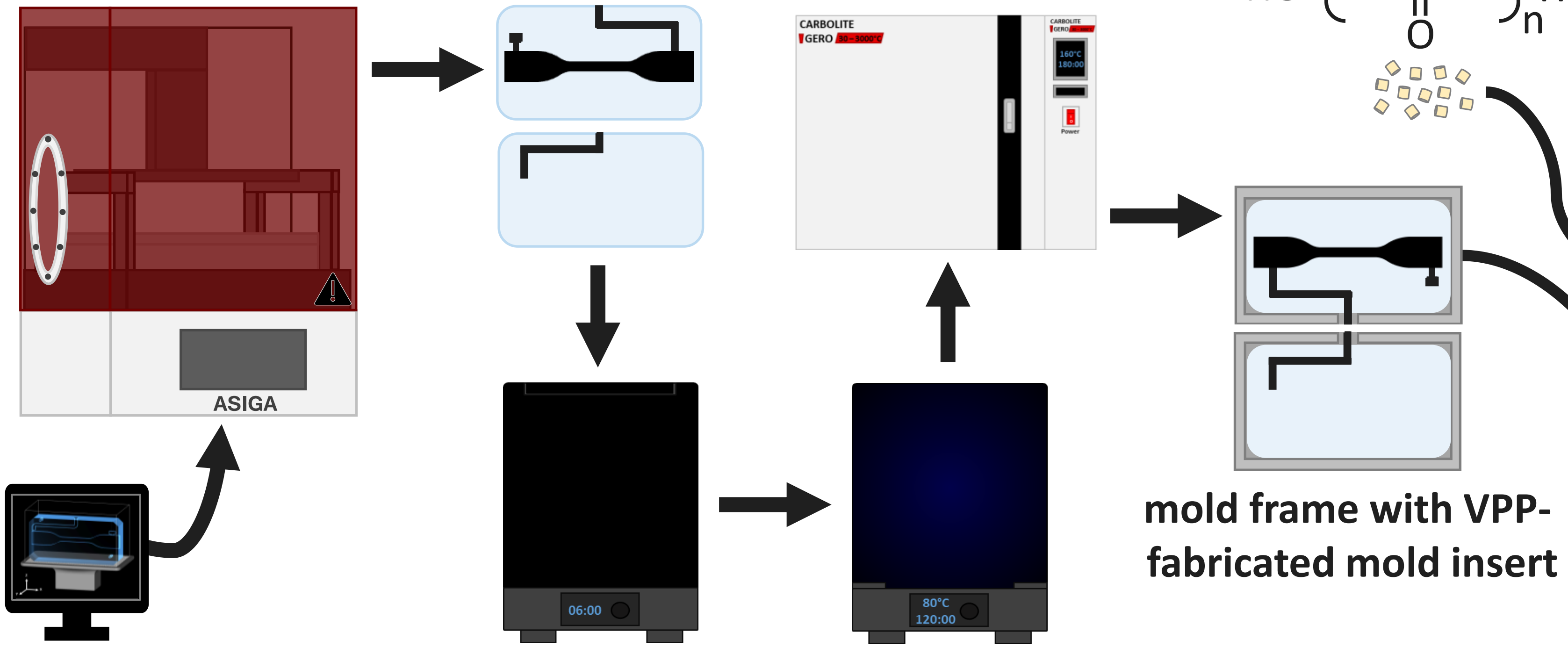
ASTM D638 type IV tensile bar specimen mold conceptualized and designed by James “Jimmy” Asbell and Mark Hudson (Advanced Manufacturing and Design Group, Advanced Engineering Division, SRNL)

Injection molding using VPP molds

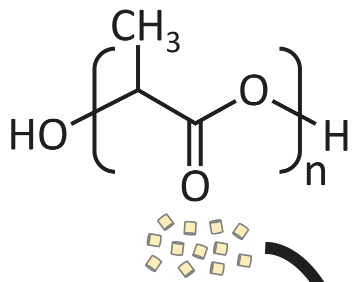
Injection molding performed by Andrew Rhodes (Advanced Manufacturing and Design Group, Advanced Engineering Division, SRNL)

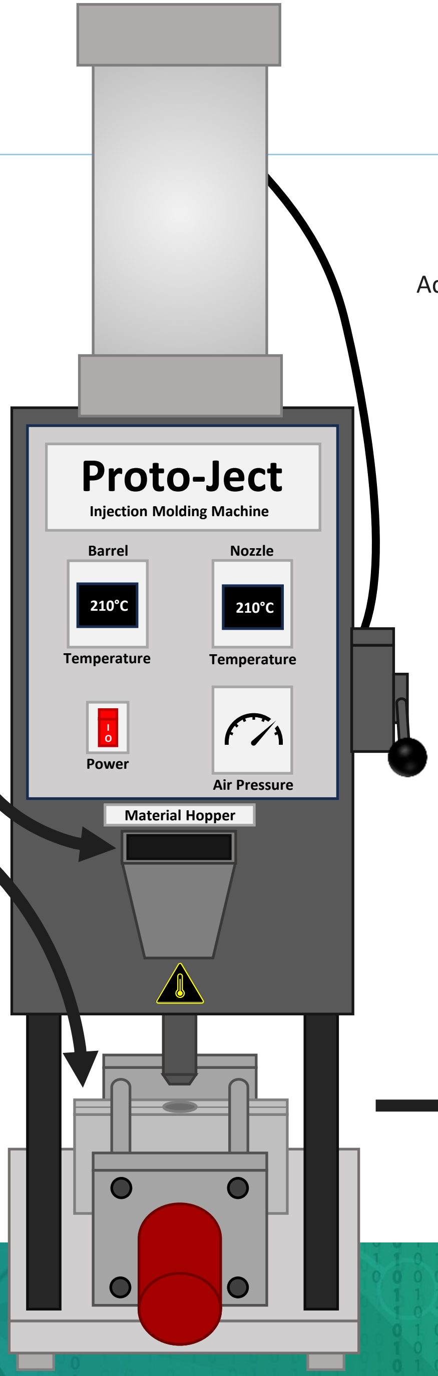
Manning Innovations Proto-Ject Benchtop Injection Molding Machine

- Injection molded poly(lactic acid) (PLA) pellets
- 210°C nozzle temperature
- 80°C mold temperature
- 3300 psi injection pressure



PLA pellets





PLA Type IV tensile bar specimens

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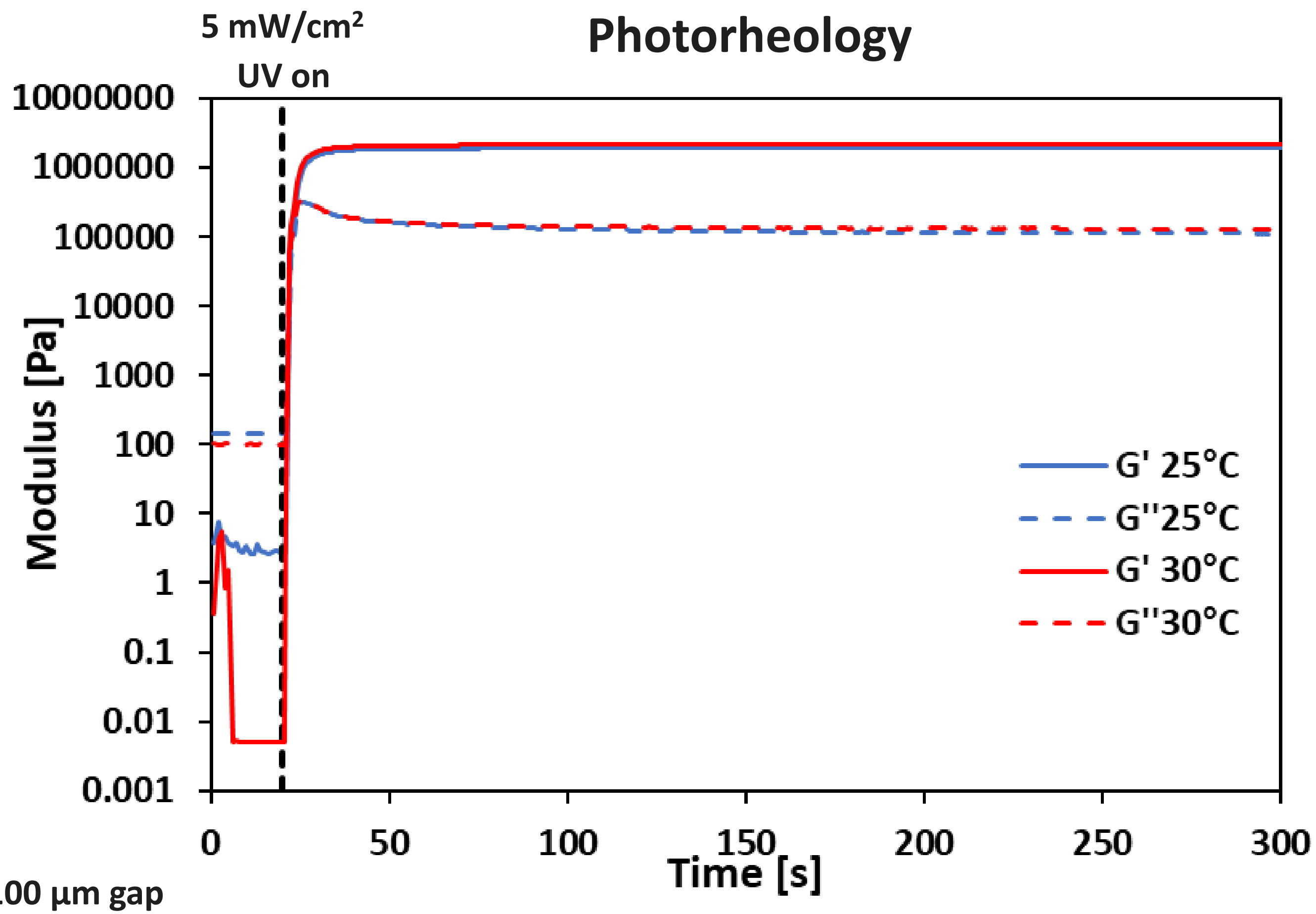
Resin characterization



100 µm gap
1% strain
10 Hz osc frequency

- Time to reach 90% of maximum storage modulus (G'):
  25°C => 16.5 s
  30°C => 18.5 s
- Time to reach 100% of maximum G':
  25°C => 290 s (1.95 MPa)
  30°C => 258 s (2.22 MPa)

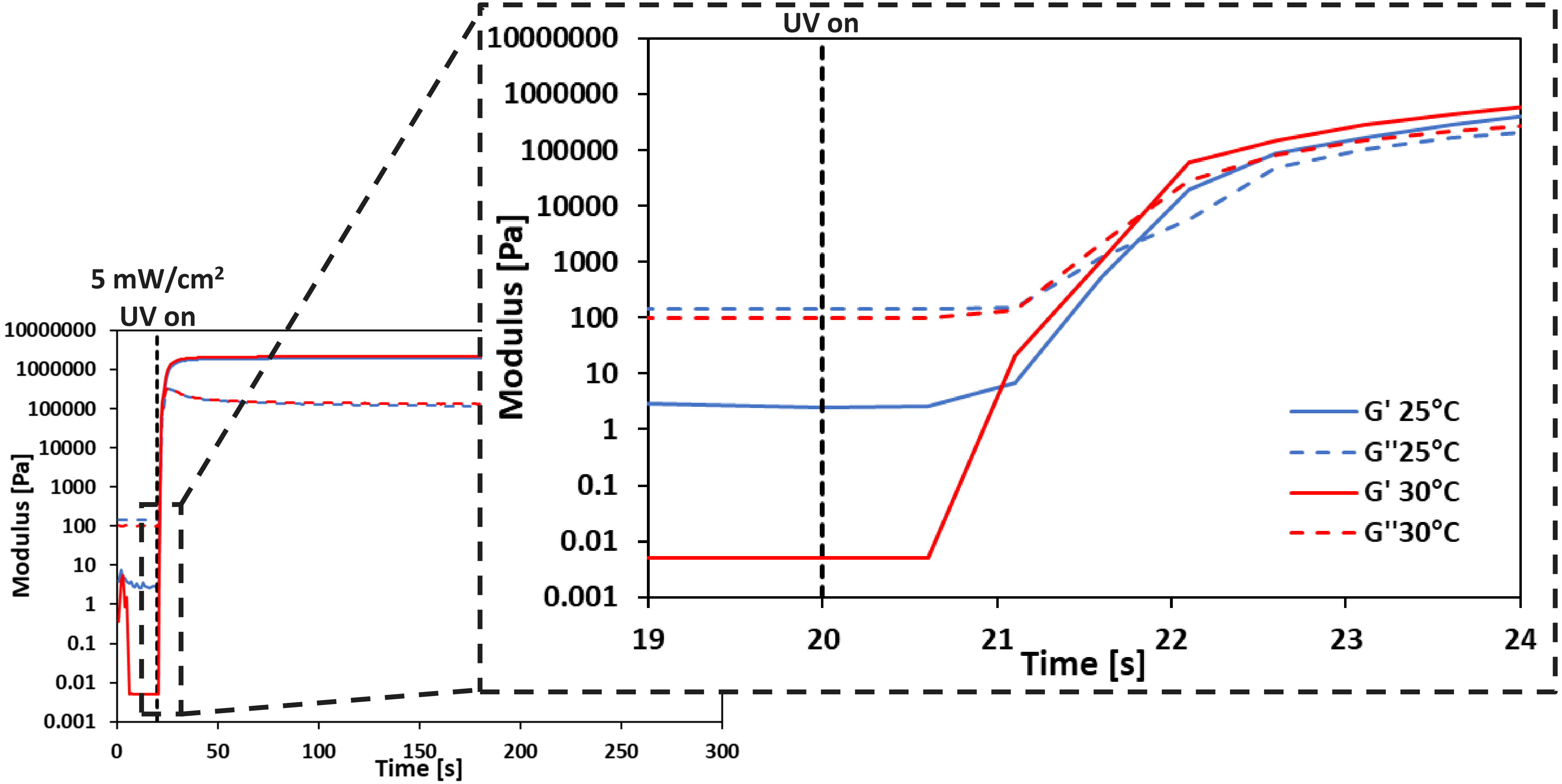
14% increase in G' at 30°C

- Complex viscosity (η*):
  25°C => 2275 cP
  30°C => 1628 cP

28% decrease in η* at 30°C

Resin characterization

Photorheology



- Time to gelation:
  25°C => 1.53 s
  30°C => 1.52 s

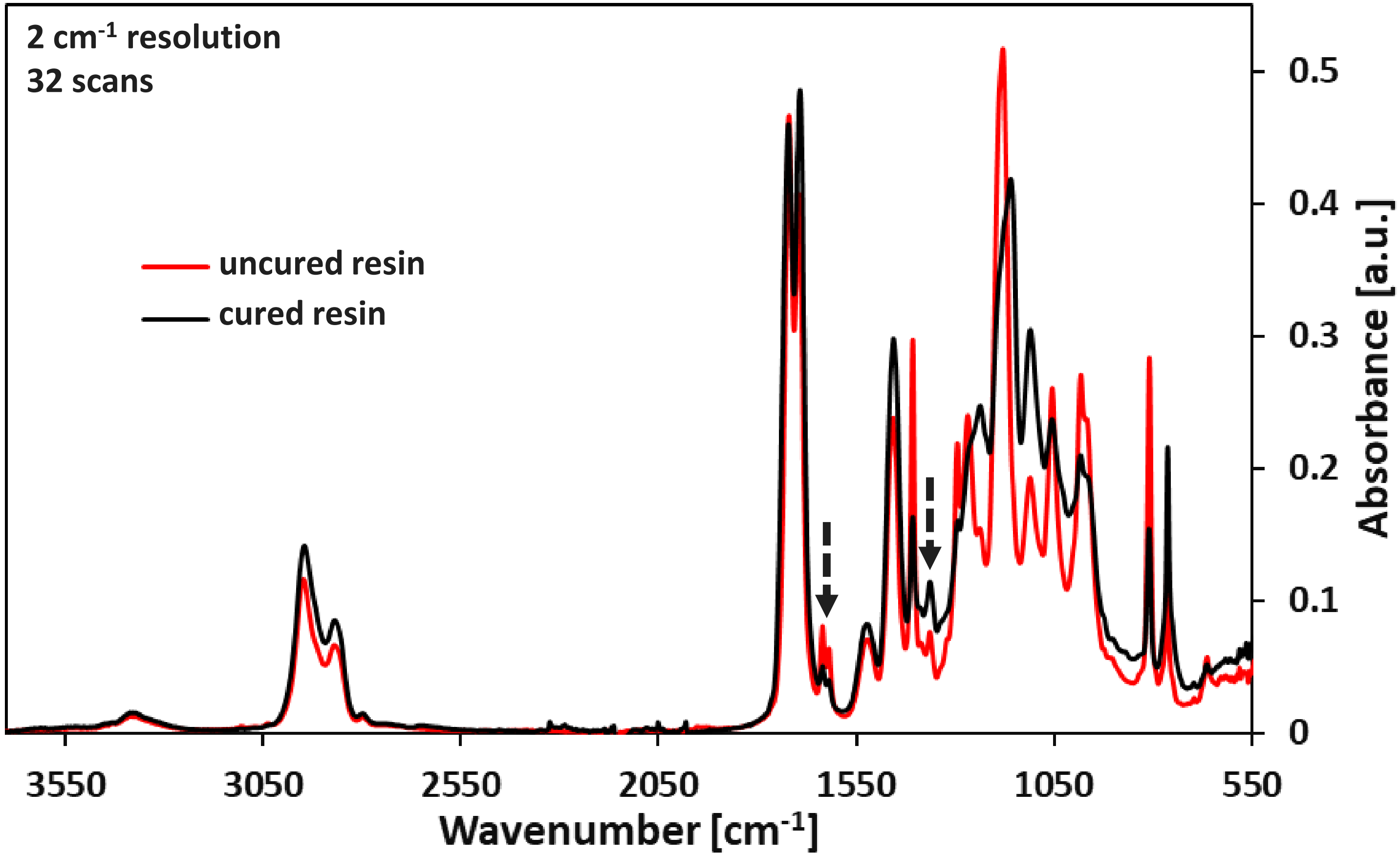
100 µm gap
1% strain
10 Hz osc frequency

Resin characterization

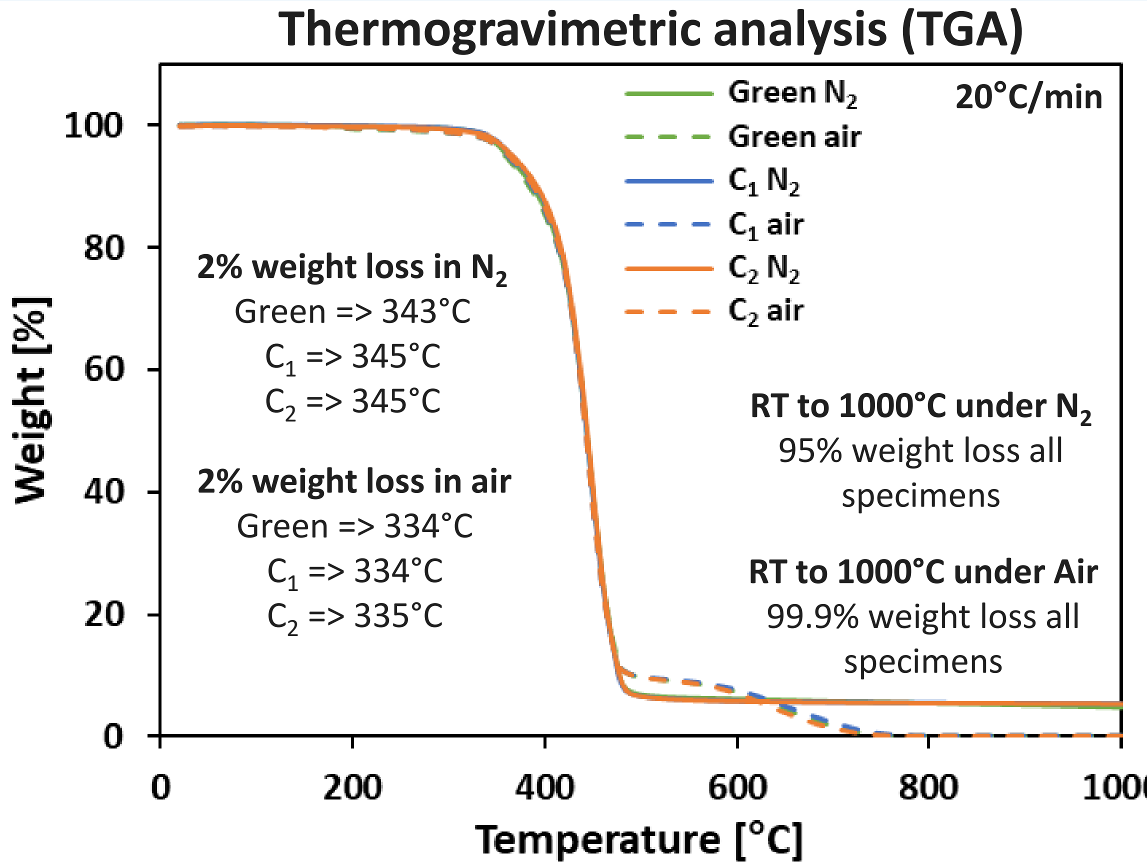
- ATR-FTIR performed on 100 um film cured on the rheometer at 30°C

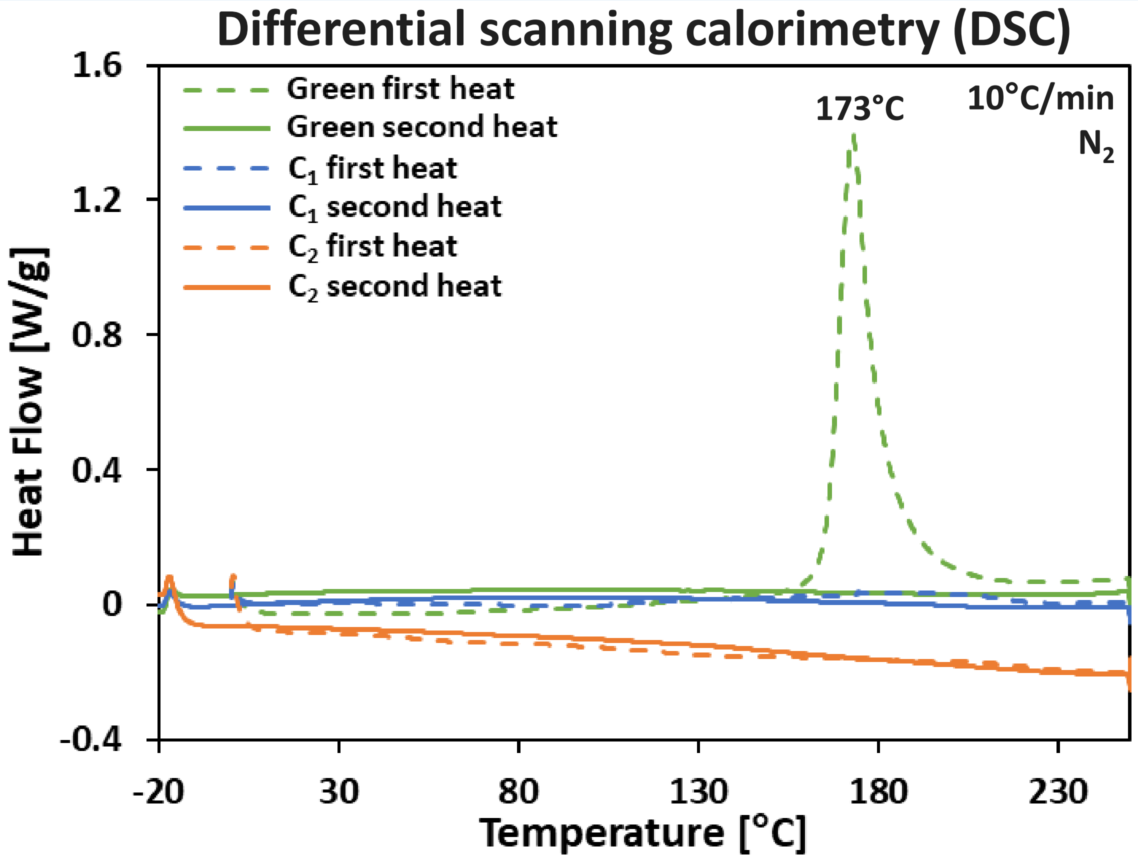
- Decreased peak intensity of cured resin at:
  1635 cm^{-1} attributed to C=C
  1407 cm^{-1} attributed to $=CH_2$

Attenuated total reflectance (ATR) – Fourier transform infrared spectroscopy (FTIR)



VPP-printed resin characterization





Additional curing only observed in the first heat of the green specimen

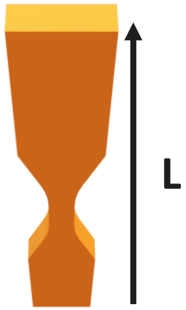
A discernable glass transition temperature (Tg) was not observed in the second heat of the green or post-cured specimens, indicating a high degree of crosslinking

VPP-printed resin characterization

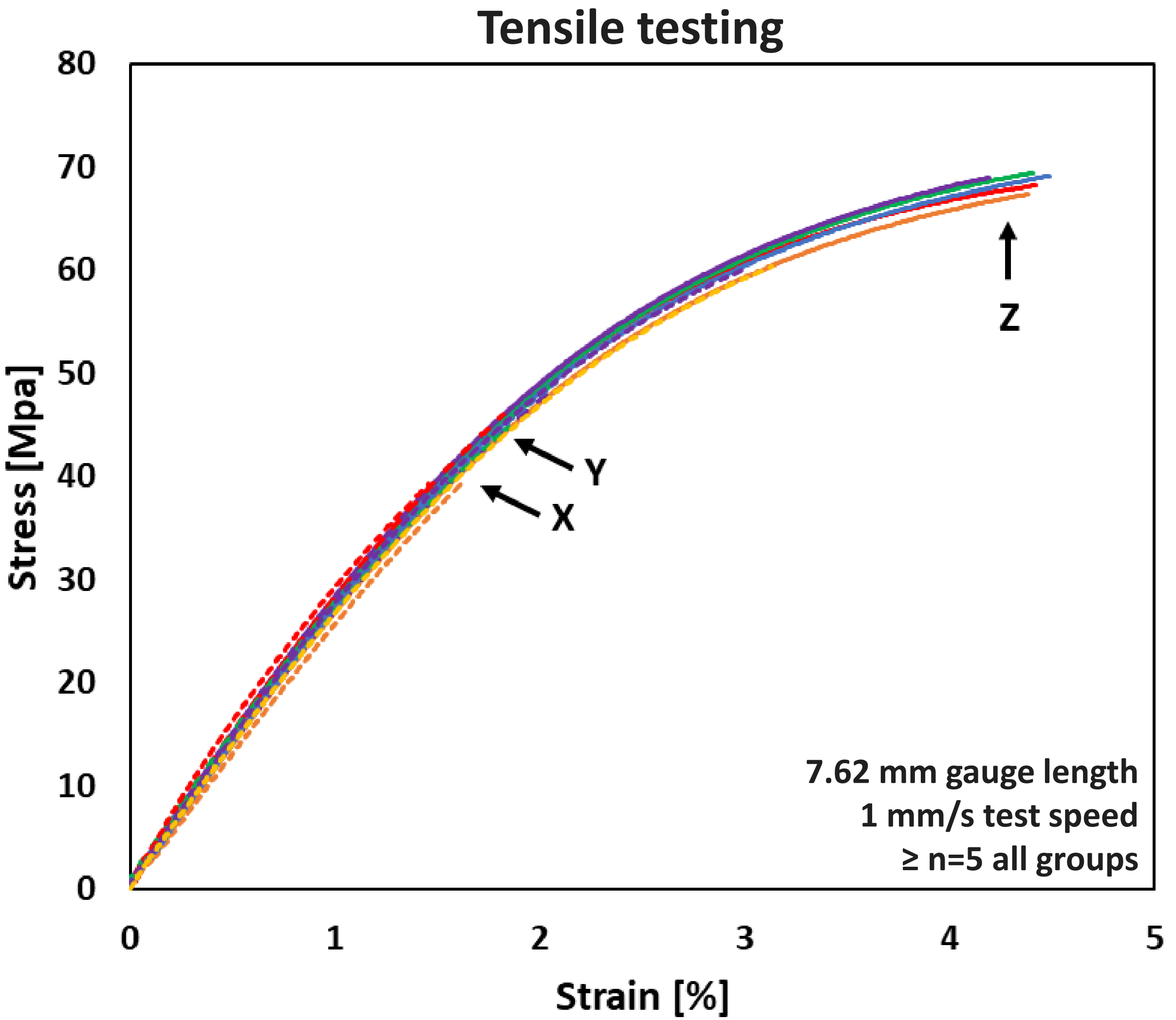
- ASTM D638 Type V tensile bar specimens

X-orientation – layers deposited along the thickness of the specimen

Y-orientation – layers deposited along the width of the specimen

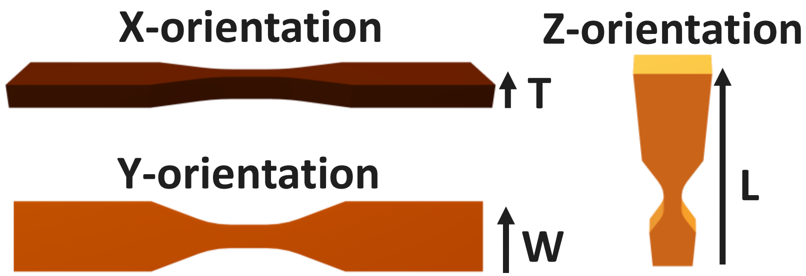


Z-orientation – layers deposited along the length of the specimen

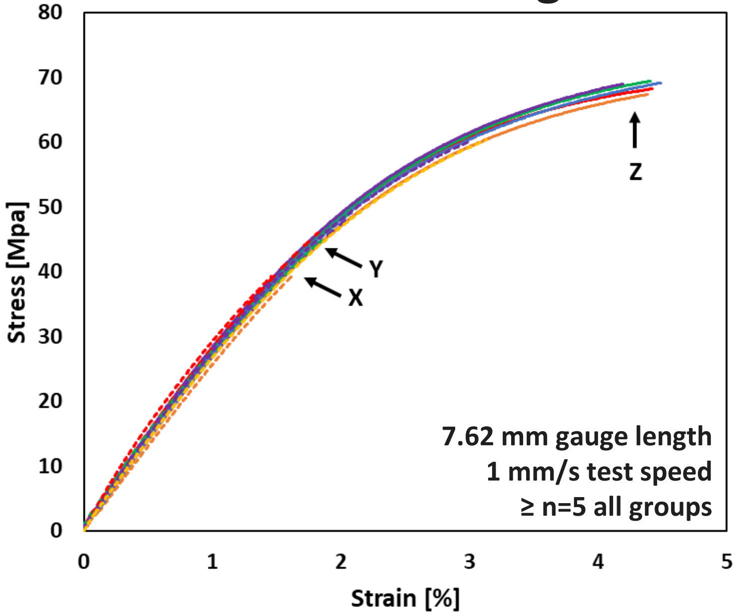


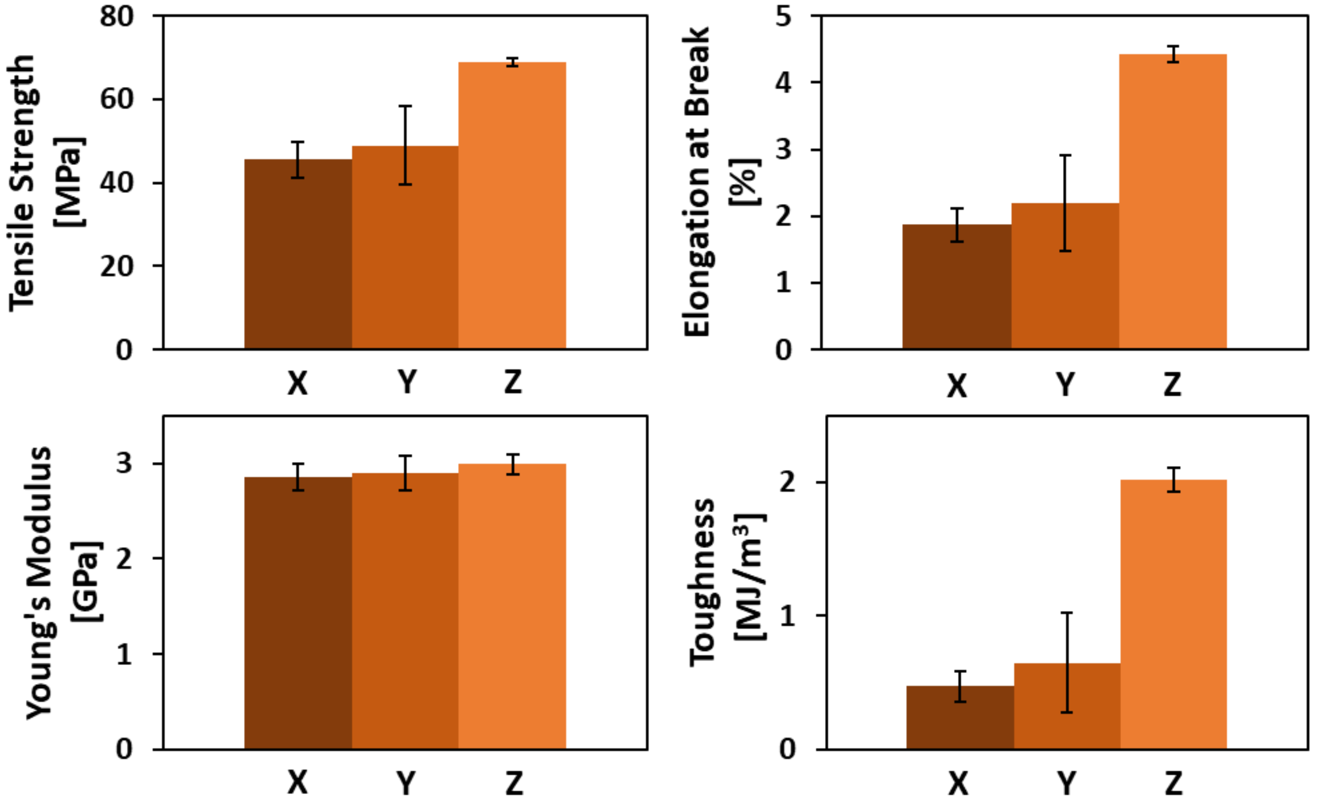
Tensile testing performed by Anastasia Mullins (Gas Transfer Systems Technology Group, Tritium Technology Division, SRNL)

VPP-printed resin characterization



Tensile testing



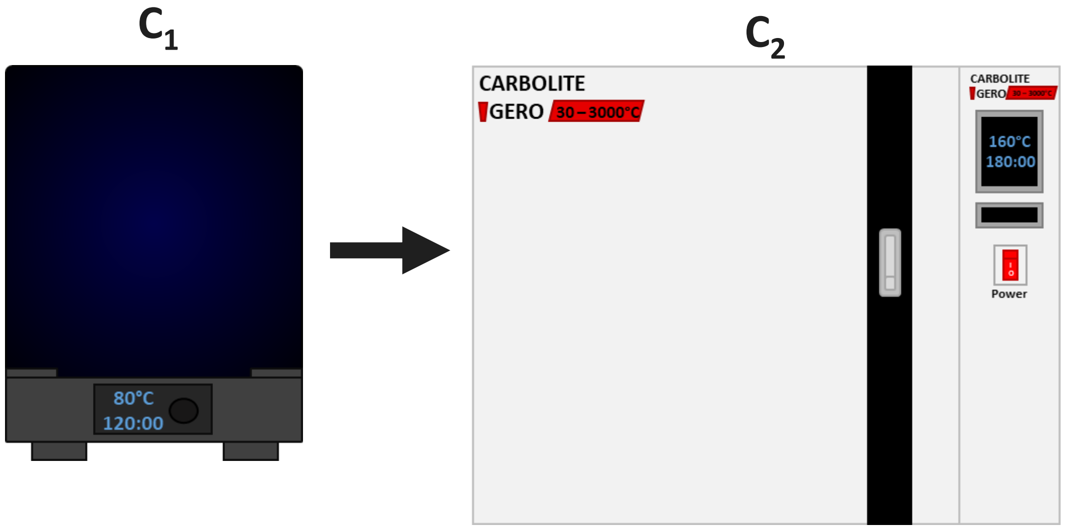


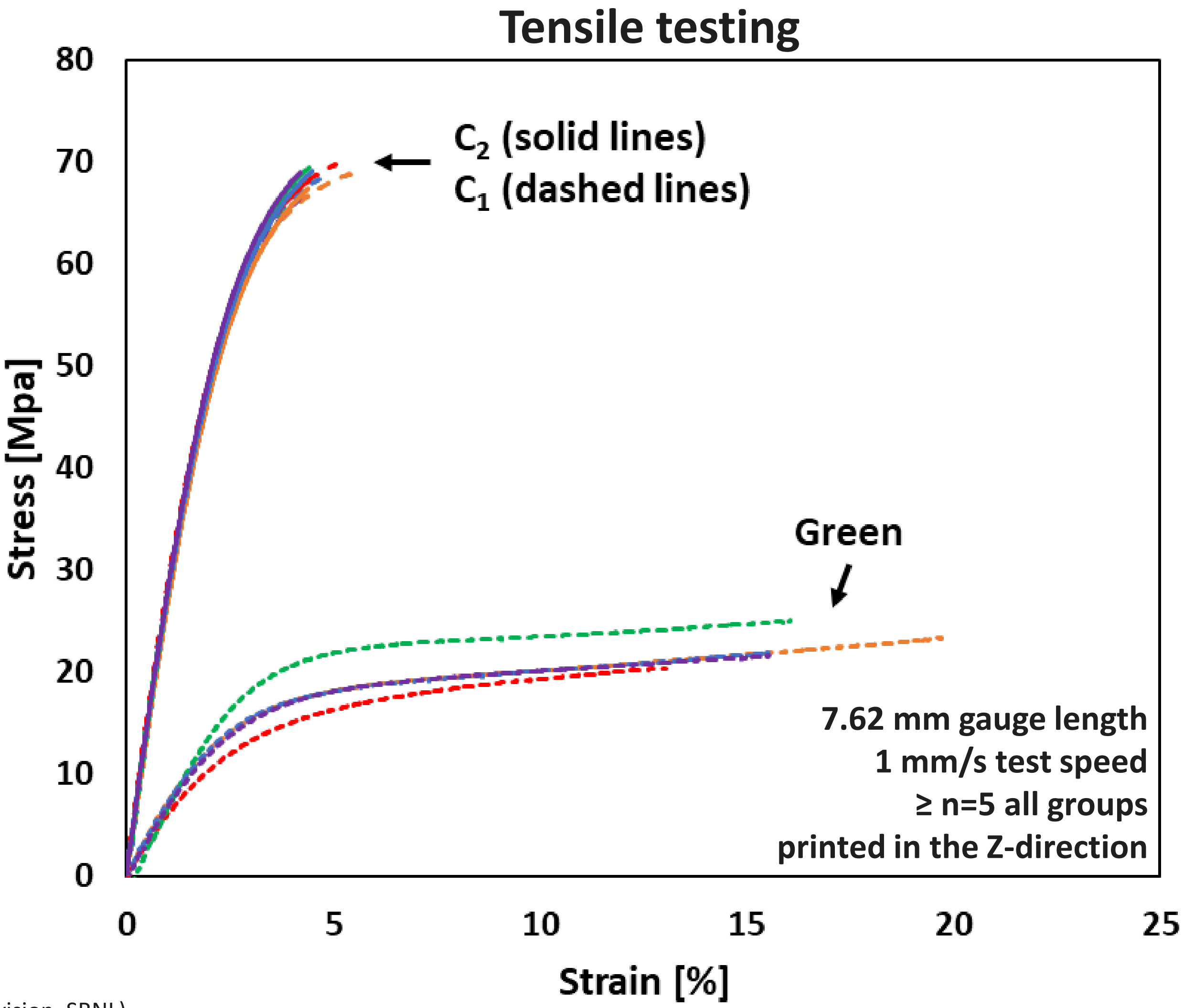
Tensile testing performed by Anastasia Mullins

Increased tensile properties of specimens fabricated in the Z-orientation – may be attributed to the reduced curing nonuniformities in the XY plane due to the smaller cross-sectional area of each layer

VPP-printed resin characterization

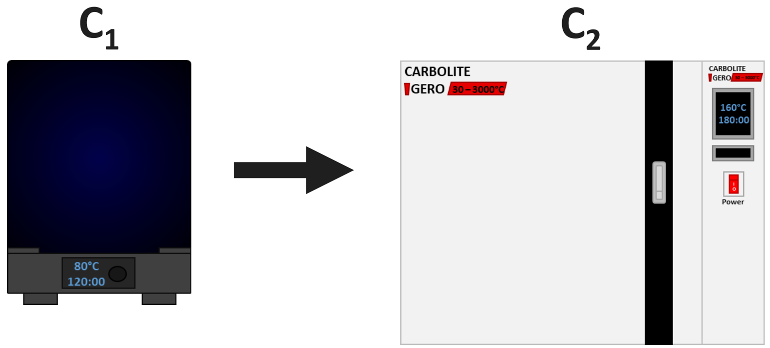
- ASTM D638 Type V tensile bar specimens



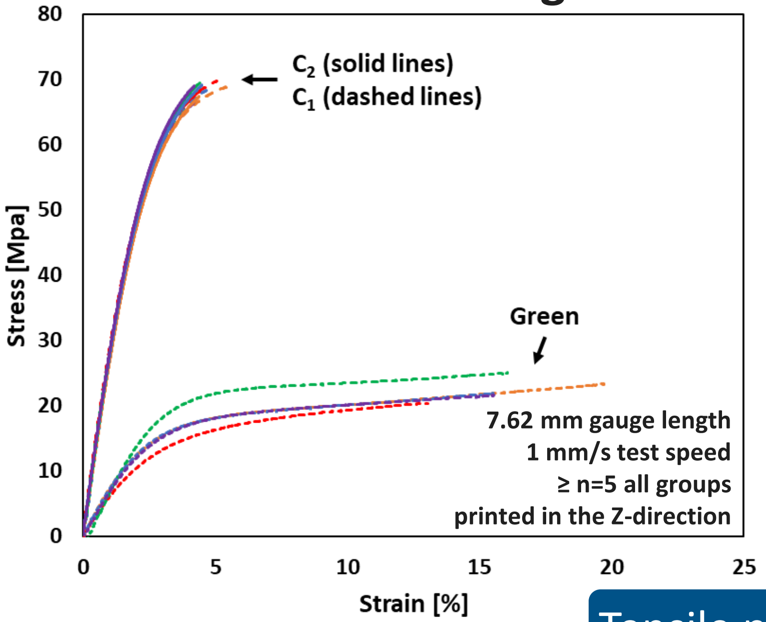


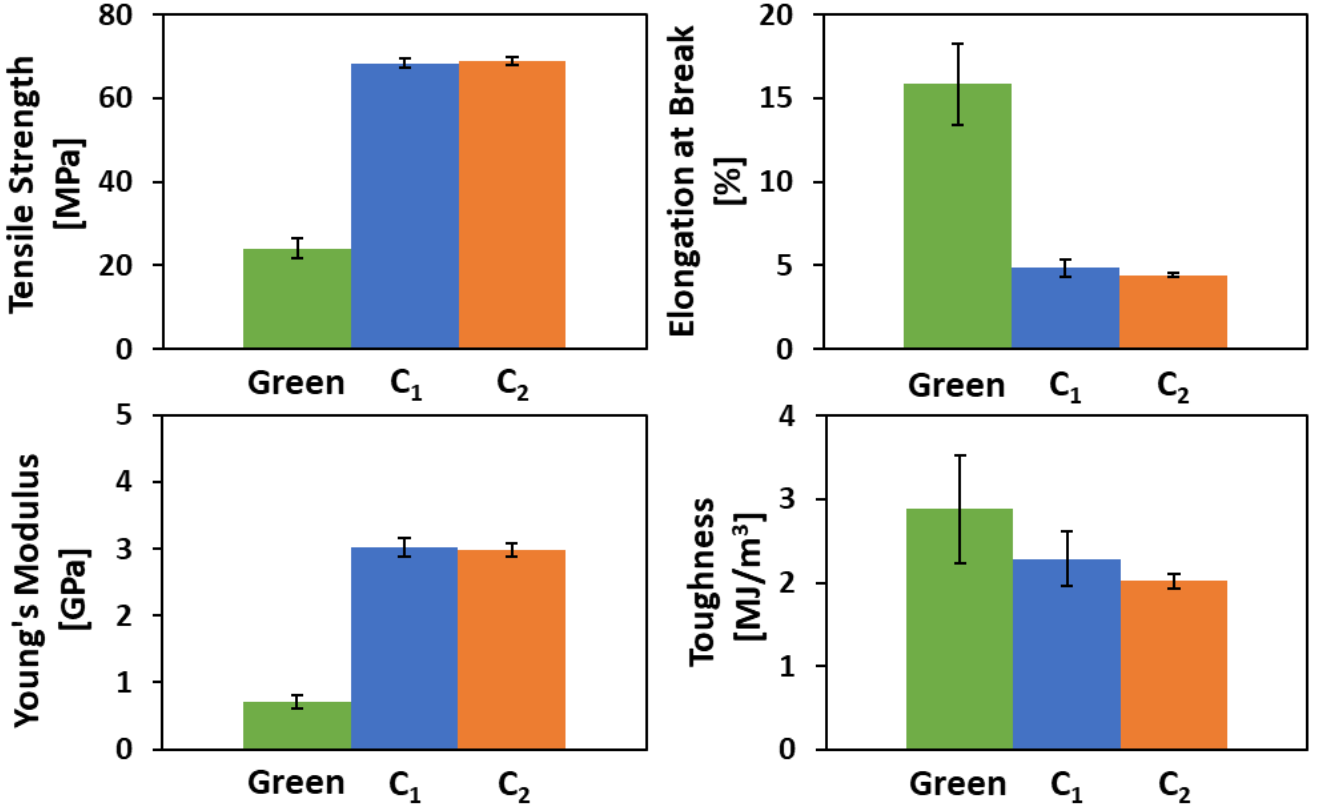
Tensile testing performed by Anastasia Mullins (Gas Transfer Systems Technology Group, Tritium Technology Division, SRNL)

VPP-printed resin characterization



Tensile testing



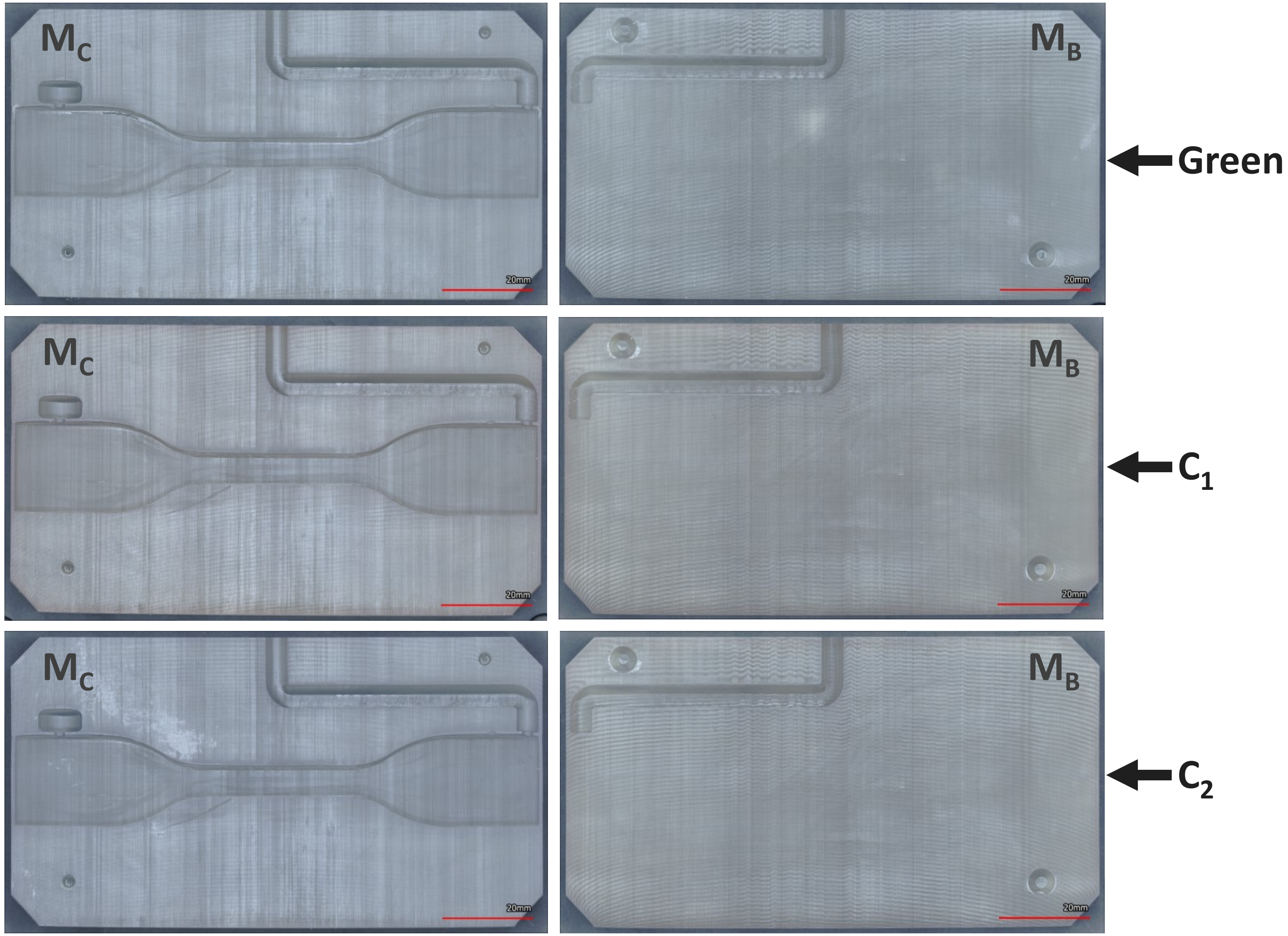


A significant increase in mechanical properties was observed after post-curing

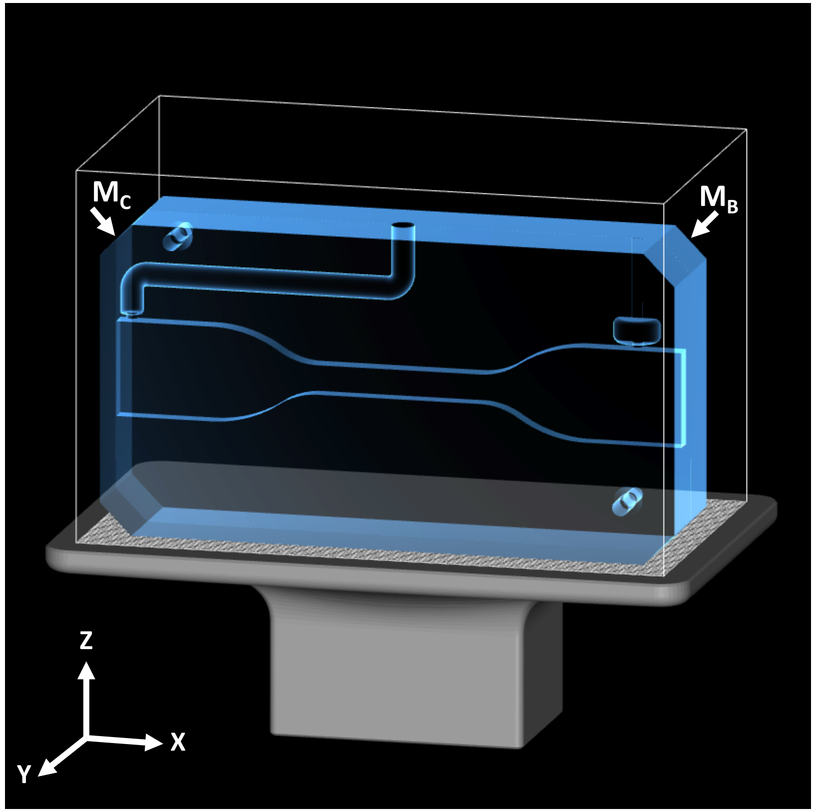
Tensile properties of specimens that underwent C_1 and C_2 post-cure treatments were comparable

Tensile testing performed by Anastasia Mullins

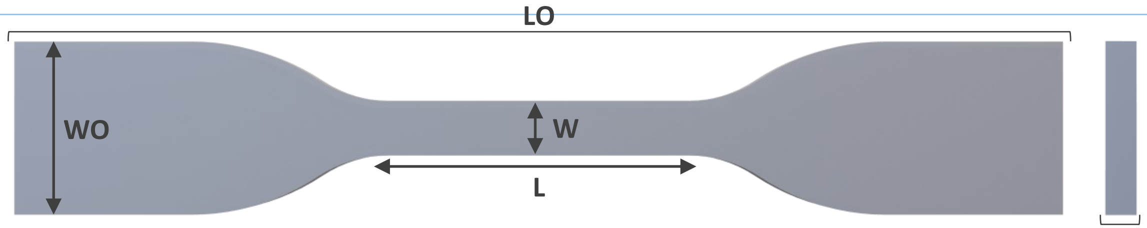
VPP-printed mold characterization



ASTM D638 Type IV tensile bar specimen mold



VPP-printed mold characterization



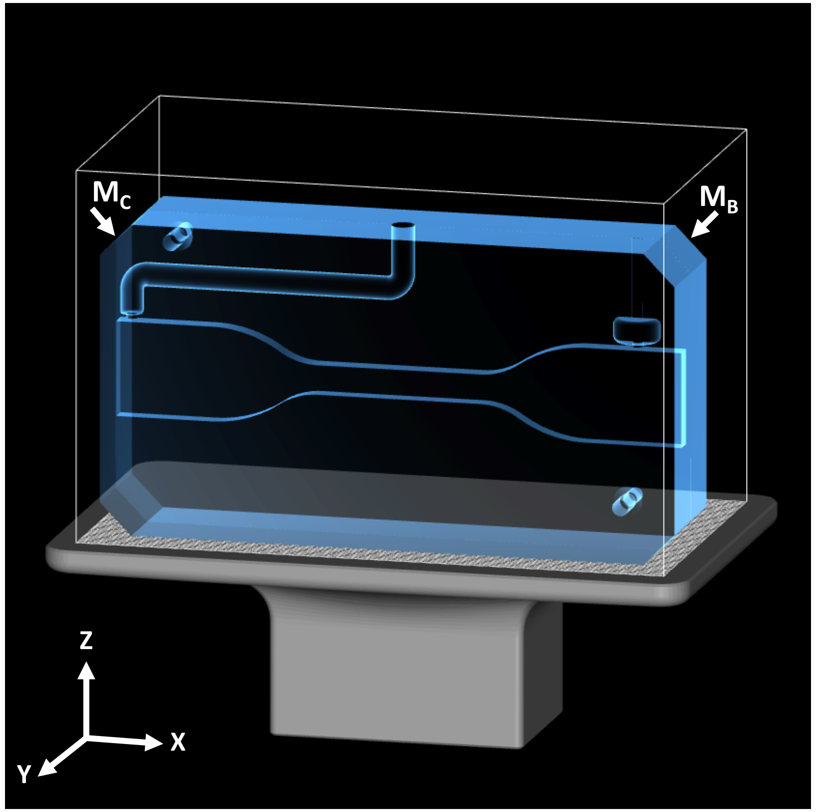
	W [mm]	L [mm]	WO [mm]	LO [mm]	T [mm]	Sa [µm]
As-designed	6.0	34.0	19.45	115.0	3.7	N/A
Green	5.5 ± 0.2	34.2 ± 0.3	18.8 ± 0.6	114.9 ± 0.4	3.7 ± 0.1	1.9 ± 0.7
C_1	5.6 ± 0.1	34.2 ± 0.1	19.6 ± 0.5	115.1 ± 0.1	3.6 ± 0.1	2.0 ± 0.9
C_2	5.8 ± 0.1	34.2 ± 0.2	19.4 ± 0.3	115.6 ± 0.5	3.6 ± 0.1	1.9 ± 0.7
% Difference from As-Designed	-5.7%	0.6%	-0.9%	0.2%	-1.5%	N/A

Tensile bar cavity dimensions in the X-direction (L, LO) showed high dimensional fidelity

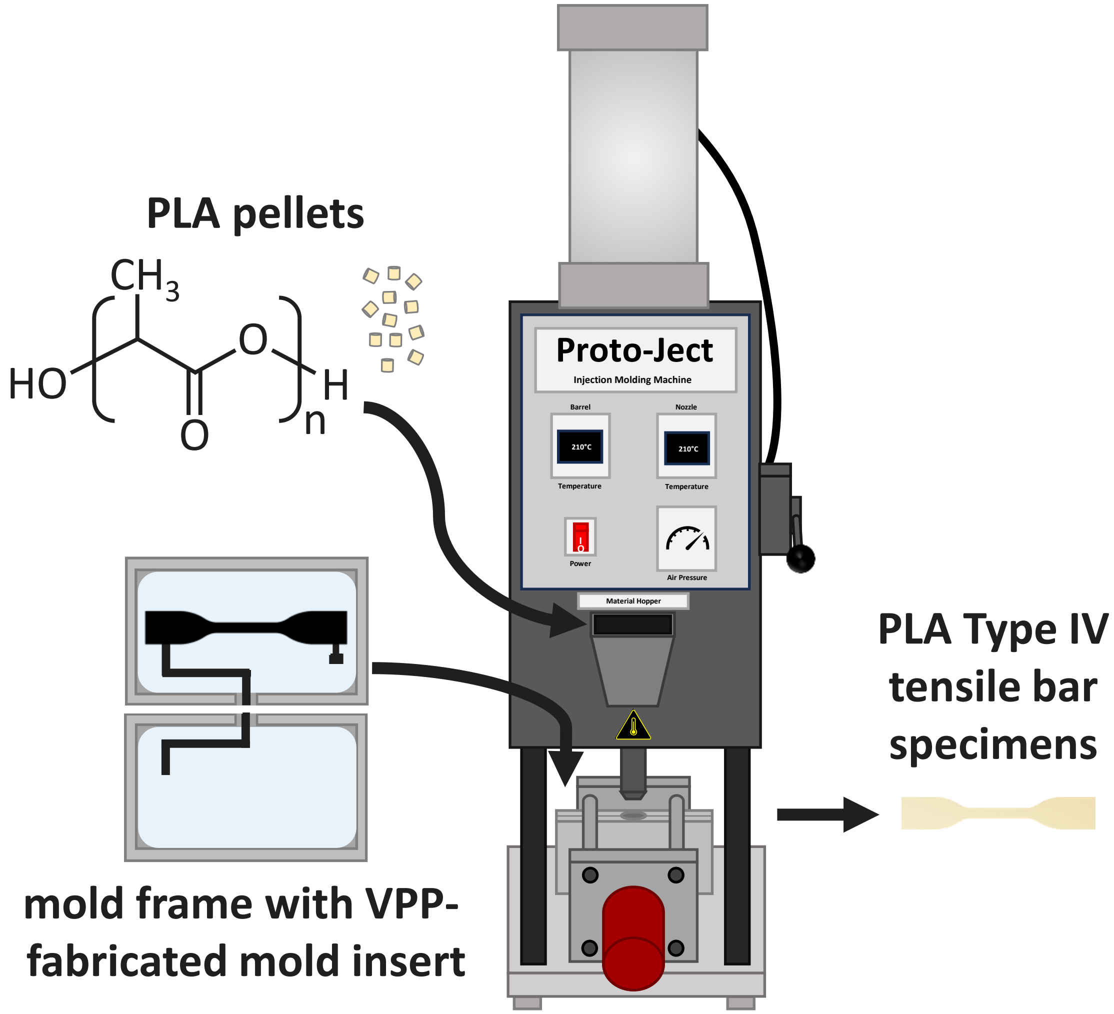
Tensile bar cavity dimensions in the Y- (T) and Z- (W, WO) directions showed high dimensional fidelity

Smooth surface finish compared to other AM techniques

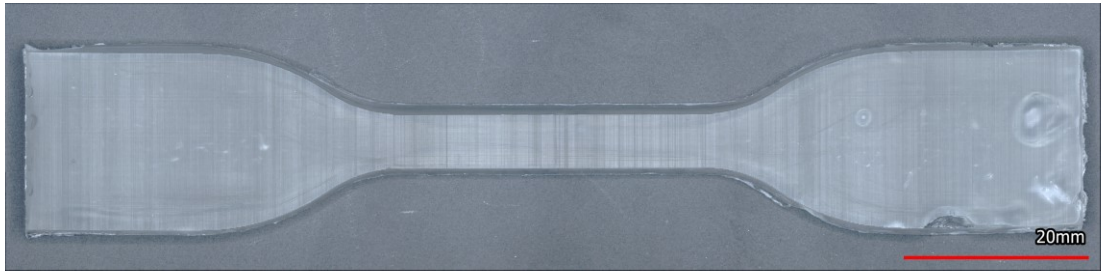
ASTM D638 Type IV tensile bar specimen mold



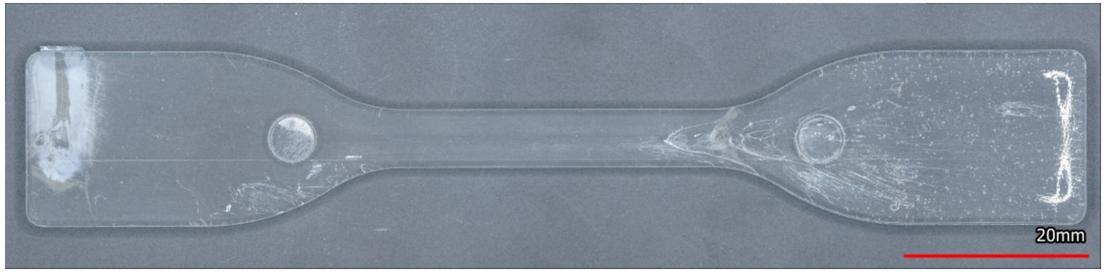
Injection molded specimens



PLA Type IV tensile bar specimen using a VPP-fabricated mold

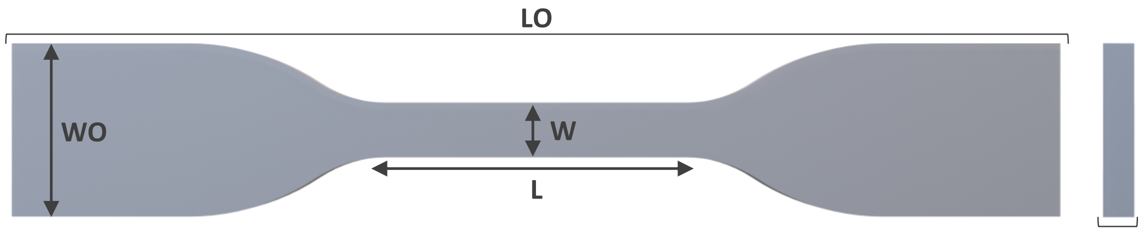


PLA Type IV tensile bar specimen using a metal mold



Injection molding performed by Andrew Rhodes (Advanced Manufacturing and Design Group, Advanced Engineering Division, SRNL)

Injection molded specimens



	W [mm]	L [mm]	WO [mm]	LO [mm]	T [mm]	Sa [µm]
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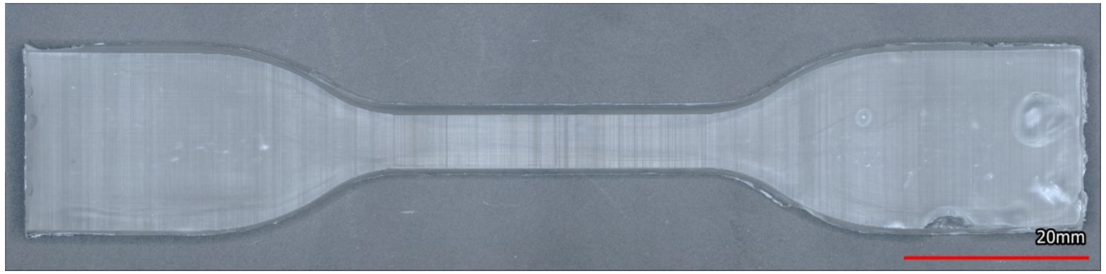
Mold	5.7 ± 0.2	34.2 ± 0.2	19.3 ± 0.5	115.2 ± 0.4	3.7 ± 0.1	1.9 ± 0.7
Injected Tensile Bar	5.7 ± 0.2	34.6 ± 0.1	19.3 ± 0.2	114.6 ± 0.2	3.7 ± 0.1	8.8 ± 2.0
% Difference from Mold	0.8%	1.0%	0.1%	-0.6%	0.5%	355%

PLA Type IV tensile bar specimen using a VPP-fabricated mold



Tensile bar mold cavity geometry was replicated by the injected PLA with high fidelity (± 1%)

Surface roughness of the injected specimen was higher than the mold itself

Trapped air suggests a need for optimized injection parameters and mold design

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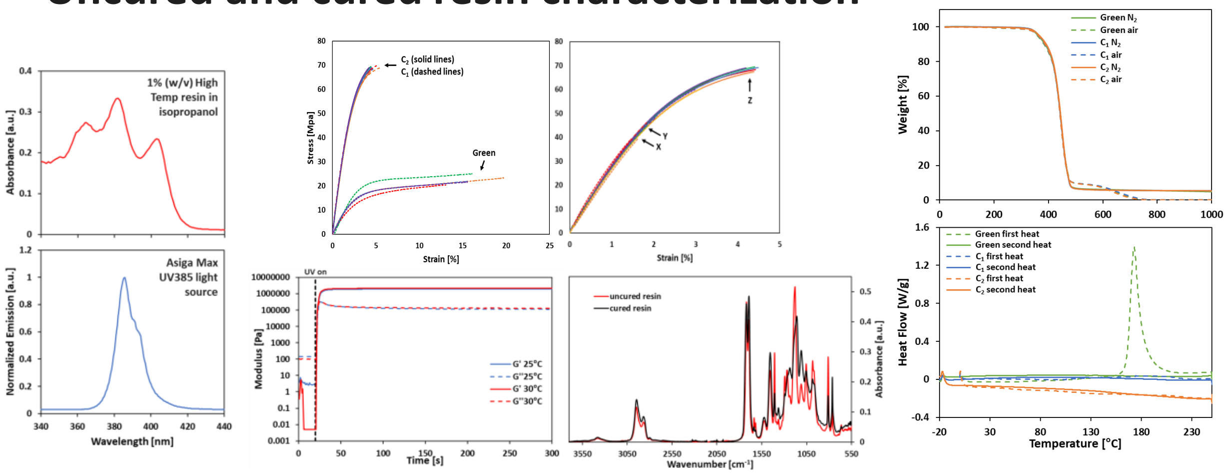
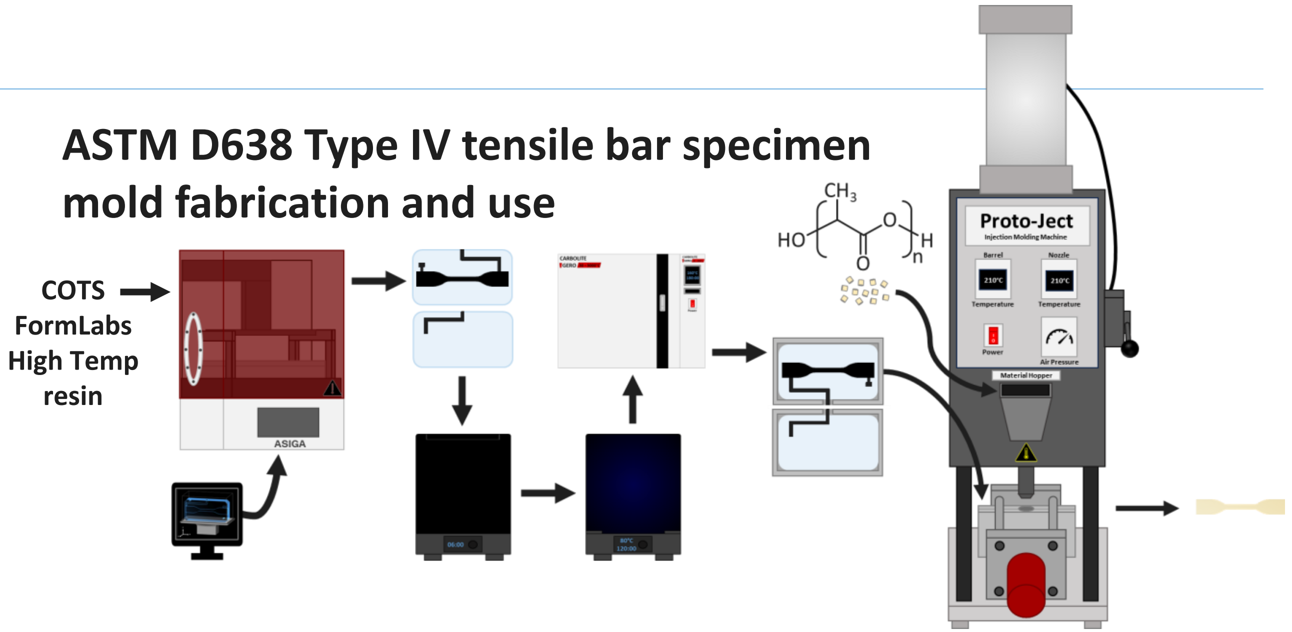
Summary

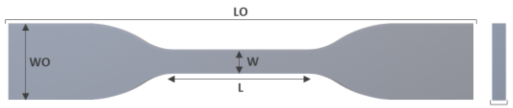
Uncured and cured resin characterization



ASTM D638 Type IV tensile bar specimen mold fabrication and use



VPP-printed mold characterization



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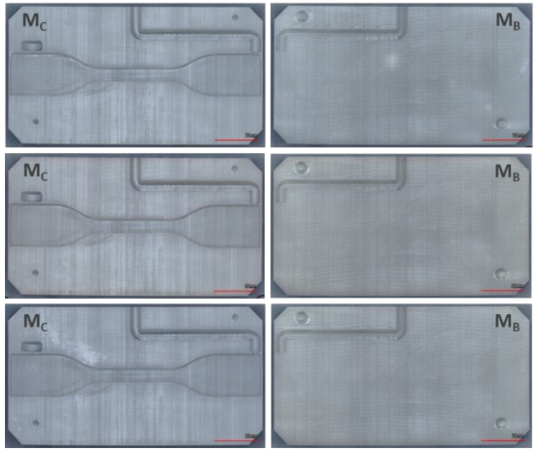
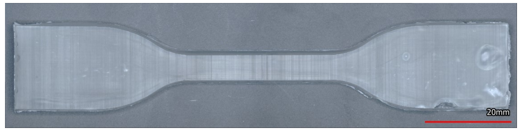
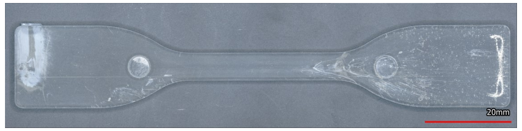


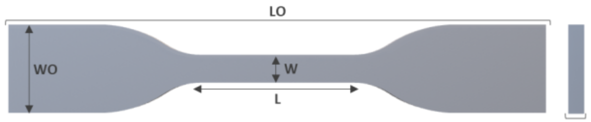
Injection molded PLA specimen characterization

PLA Type IV tensile bar specimen using a VPP-fabricated mold



PLA Type IV tensile bar specimen using a metal mold





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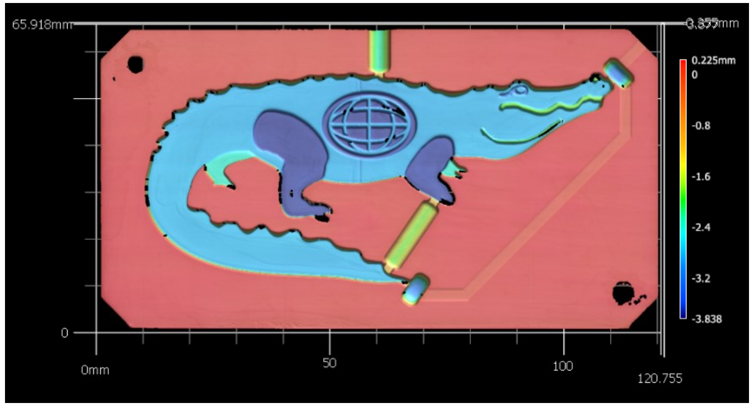
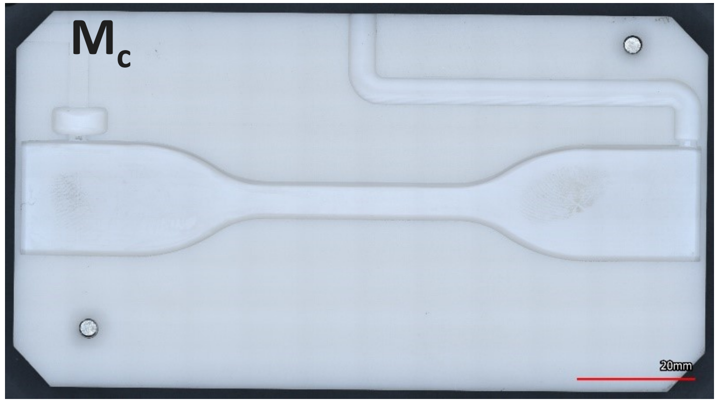
Future Work

- Evaluation of VPP-fabricated molds after one and multiple injection molding shots to assess dimensional changes
- Exploration of VPP-fabricated molds using poly(dicyclopentadiene) (pDCPD) resin (e.g., COTS PolySpectra COR Alpha resin) and ceramic-loaded resin (e.g., COTS FormLabs Rigid 10K resin) for enhanced mold performance
- VPP-fabricated molds of more complex designs and using Creo mold flow predictions



3D depth map of a mold of Savannah River Site's resident alligator, "Stumpy"



"Stumpy" mold design by Timothy Novajosky (SRNL Summer Intern; Department of Mechanical Engineering, University of Georgia, Athens, GA USA)

Acknowledgements

SRNL Advanced Engineering –
Advanced Manufacturing and Design Group

Monica Phillips
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Dane Digby
Mark Hudson
James "Jimmy" Asbell
Timothy Novojovsky – SRNL Summer Intern (UGA)

SRNL Nuclear and Chemical Processing –
Chemical Flowsheet Development Group

Matthew Williams, Ph.D.

SRNL Tritium Technology –
Gas Transfer Systems Technology Group

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Advanced Manufacturing and Design Group

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Questions?