CHARACTERIZING THERMOMECHANICAL PERFORMANCE OF LARGE-FORMAT PRINTED COMPOSITE POLYMER STRUCTURES

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Oak Ridge, TN

Overview Moving Forward

- **Background**
- **Materials for Study**
- **DIC Oven Testing**
- **Mechanical Testing**
    - Dynamic Mechanical Analysis (DMA)
    - 4 Point Bend (4pt Bend)
- **Conclusions**

DIC Oven at the University of Tennessee

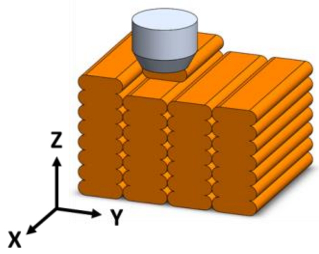
Large-Format Additive Manufacturing

- Large-Format additive manufacturing (LFAM) is advantageous for large, complex geometries
- LOCI-One type system was developed to create these large parts
- Fiber Reinforced Polymers (FRP) feedstock increases part stiffness and lowers CTE[1]

Loci Robotics Inc.'s LOCI-One System

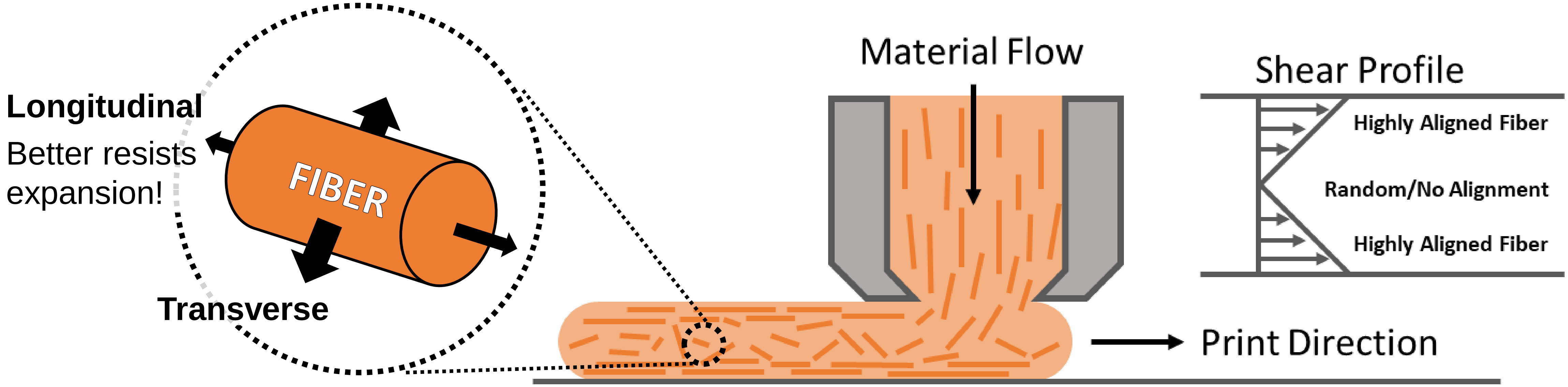
1. Love et al., 2014, DOI:10.1557/jmr.2014.212

Fiber Reinforced Polymer



Fiber Reinforced Polymer Composites = MATRIX + FIBER

- During the extrusion, fibers are aligned by nozzle shear in the print direction[1]
- This results in a highly aligned bead edge with randomly oriented center by comparison[2]
- After extrusion, the fiber aligned bead has an anisotropic cross section
- Anisotropic beads lead to a highly anisotropic mesostructure



1. Hassen et al., 2022, DOI: 10.1002/pc.26645
2. Colón Quintana et al., 2022, DOI: 10.3390/ma15082764

What influences fiber alignment?

Flow Rate, Q

- Calculated using **print speed** (v) and **bead cross-sectional area** (A)
- Increases with faster print speeds or larger bead area

$$Q = vA$$

Shear Rate, $\dot{\gamma}$

- Increases with higher **flow rate**, Q
- Higher shear rate → fibers aligned more

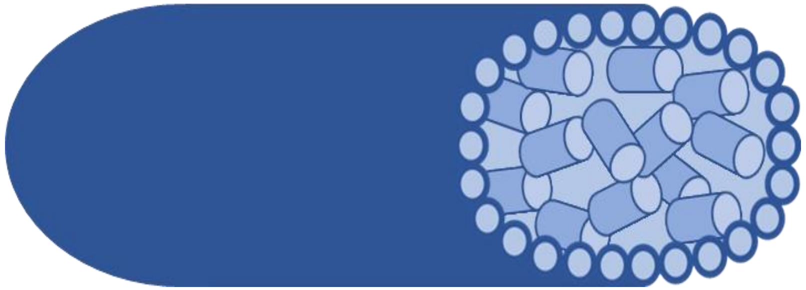
$$\dot{\gamma} = \frac{4Q}{\pi R^3}$$

where, R = nozzle radius

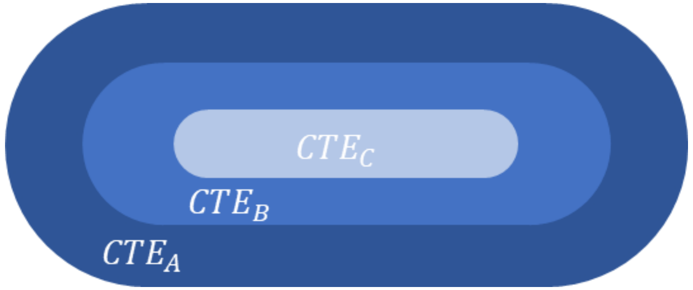
Anisotropy from Fiber Alignment

- HIGHLY anisotropic thermomechanical properties in the x, y, and z-direction
- Fibers resist expansion much more in the longitudinal than transverse direction
- Alignment causes different tiers of CTE in based on amount of alignment
    - Ex: less fiber alignment at center, lower x-dir CTE than at highly aligned edge
- Thermomechanical Analysis (TMA) does not accurately capture CTE of the complex microstructure due to size limitations as shown by previous work[1,2]

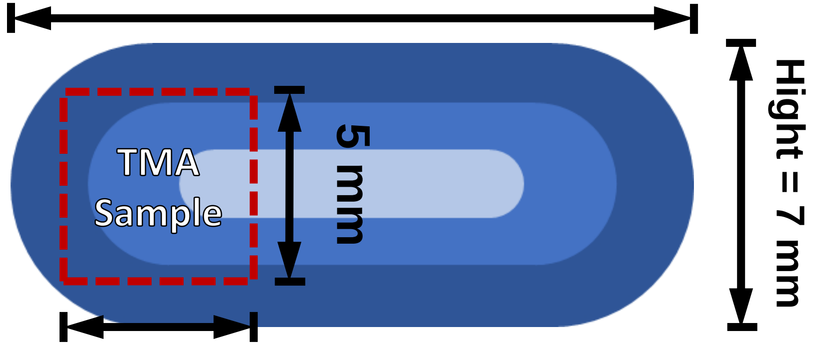
x-direction →



Where, $\mathbf{CTE_A \neq CTE_B \neq CTE_C}$



Bead Width: 15 mm

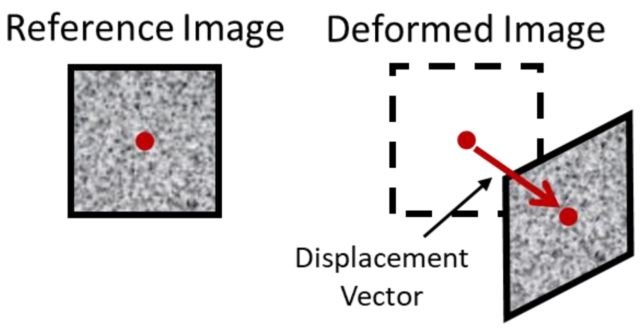


1. Corum et al., 2022, DOI: 10.26153/tsw/44338
2. Hoskins et al., 2019, DOI: 10.26153/tsw/17350

Because of the anisotropic behavior of FRP made LFAM structures, we need a better way to measure them

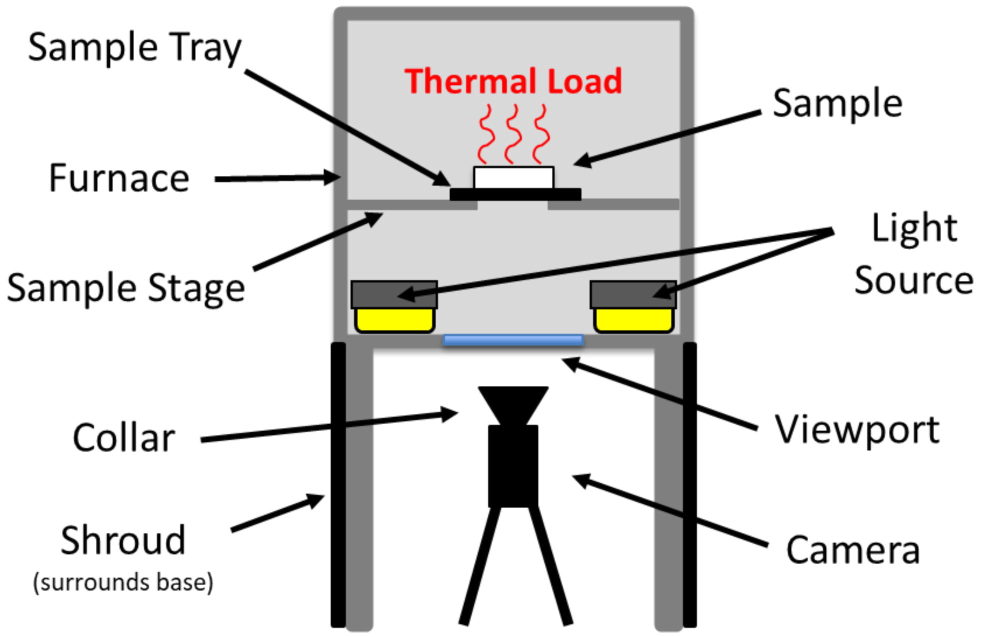
DIC Oven Overview

2D Digital Image Correlation

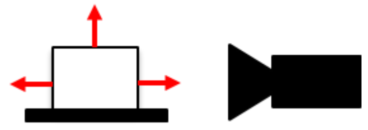


Digital Image Correlation (DIC) tracks the location of speckles from a reference to deformed state to create displacement vectors

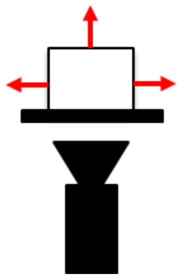
Major Components of the DIC Oven



Camera Placement



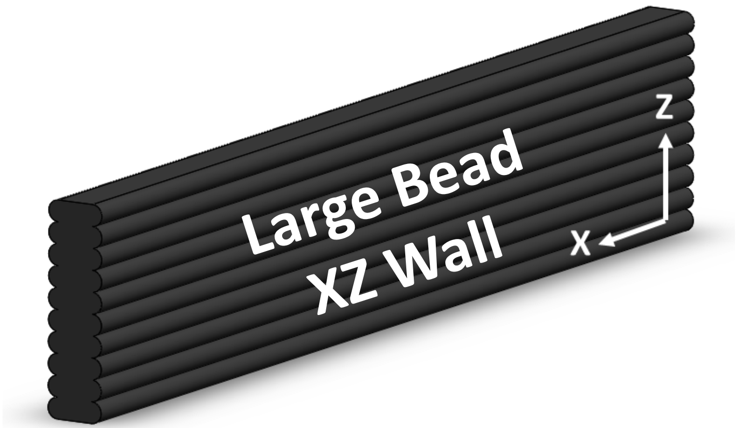
Typical 2D DIC camera placement can record expansion towards camera as false strain



DIC Oven camera placement greatly reduces chances of capturing false strain

Objectives of this Study

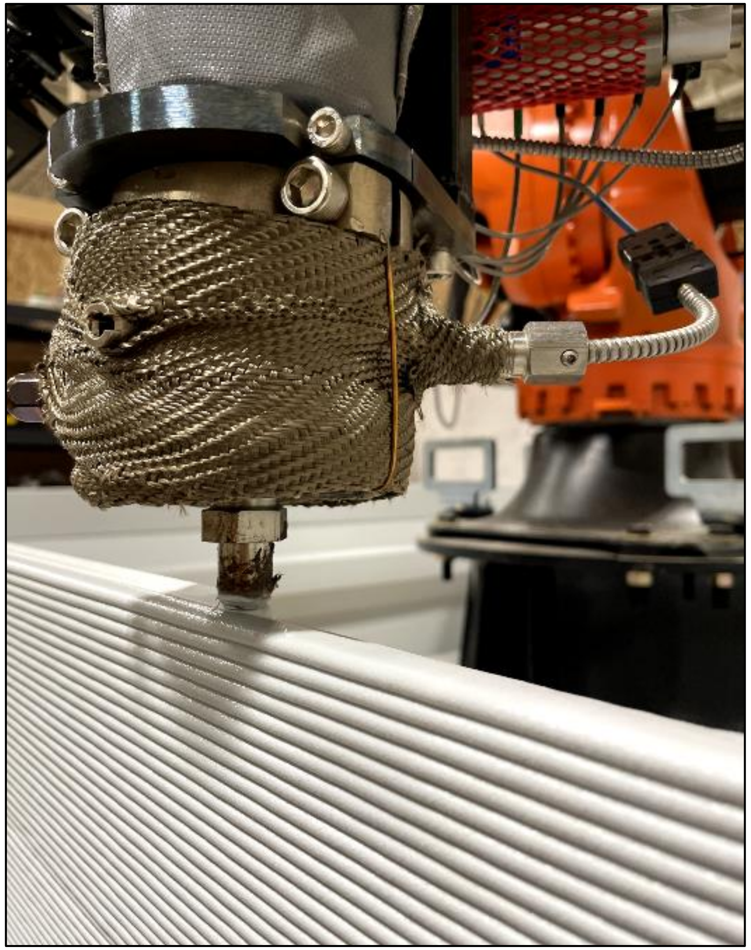
Characterize CTE, stiffness, & layer bonding based on print parameters of bead geometry, layer time, & print speed for LFAM structures



Loci Robotics Inc.

Loci Robotics Inc. is a Knoxville based company produces these LFAM type printers

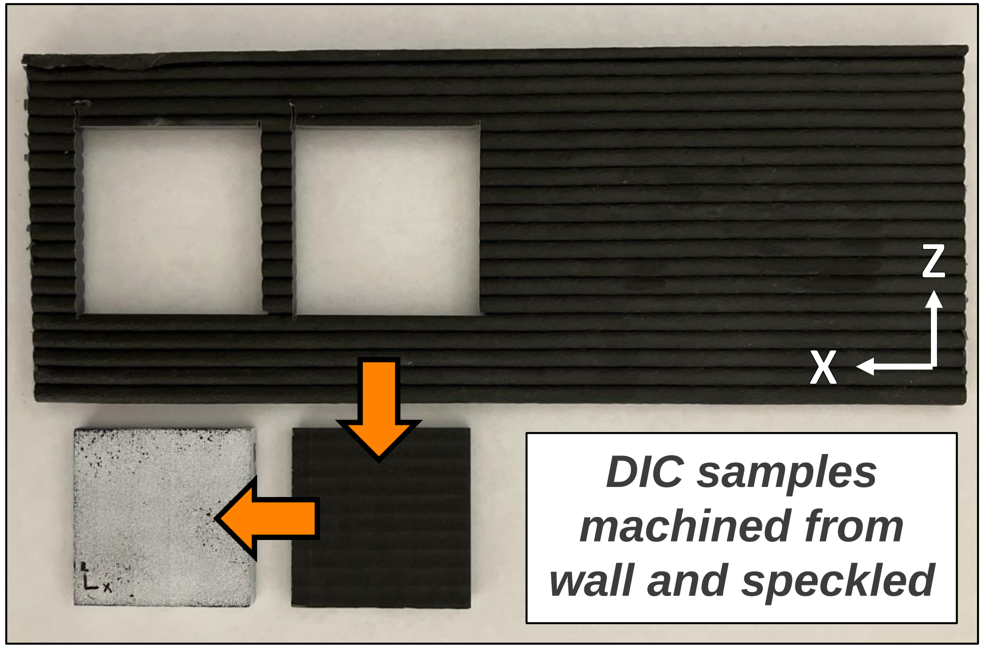
- The LOCI One system utilizes the precision of a Kuka 6-axis robot arm
- Single screw extruder nozzle assembly

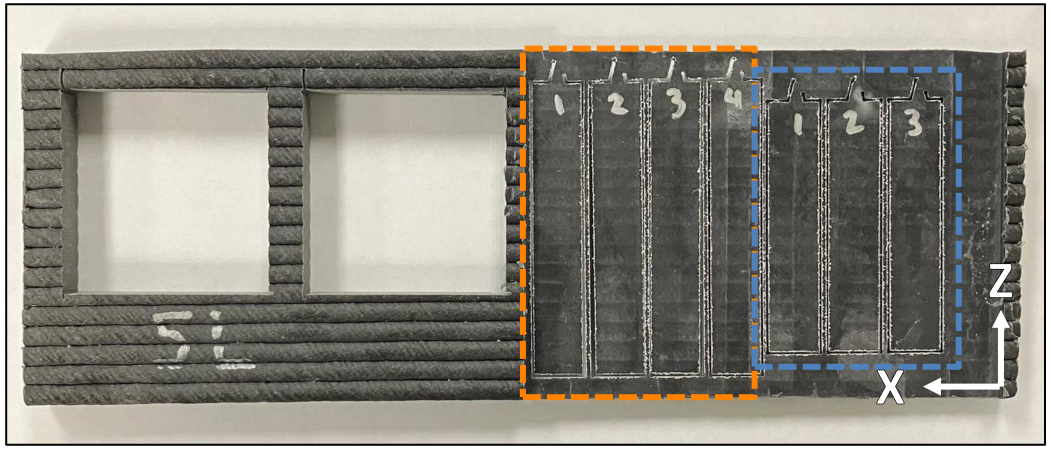


LOCI-One System

Material

- Printed using Loci-One system
- 20% CF-ABS feedstock
- XZ Wall structures printed (single bead thick)
  - 2”x2” plates cut from printed walls for DIC Oven testing
  - DMA sample dimensions of 64x13x3mm
  - 4pt bend sample dimensions of 70x12.7x3 mm

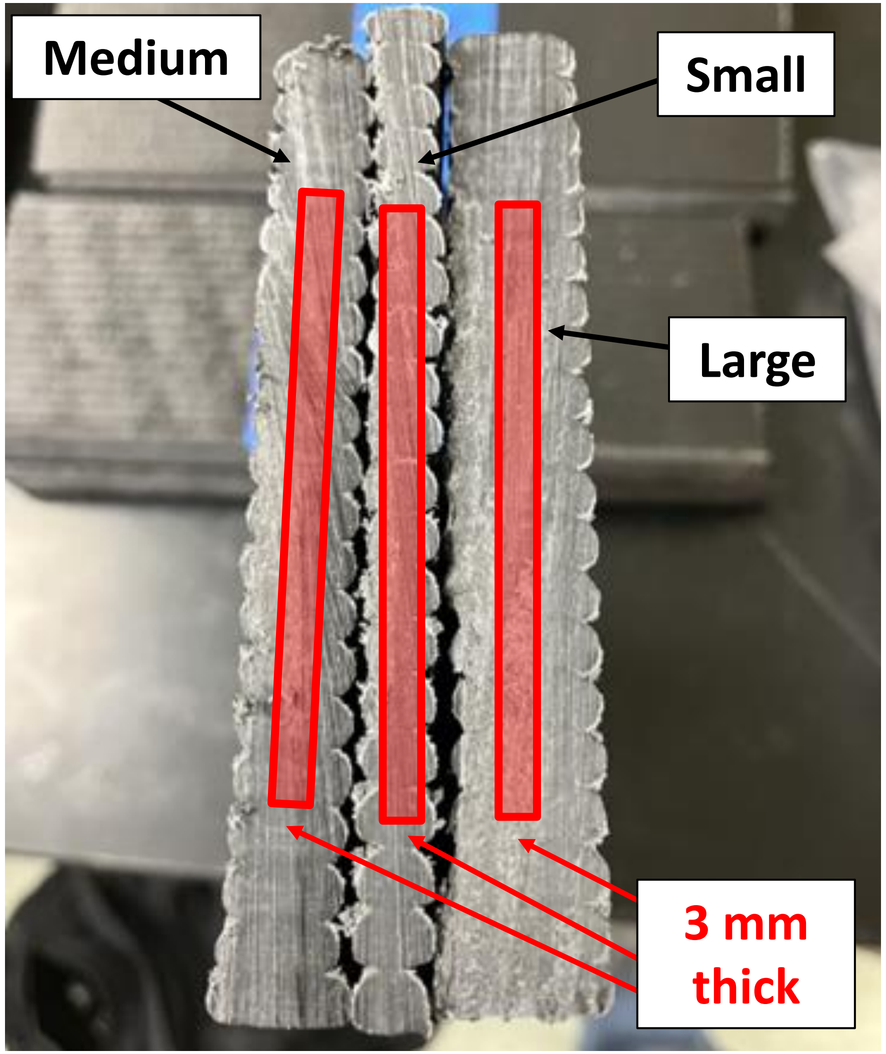




The 4pt Bend and DMA sampling shown here

Material

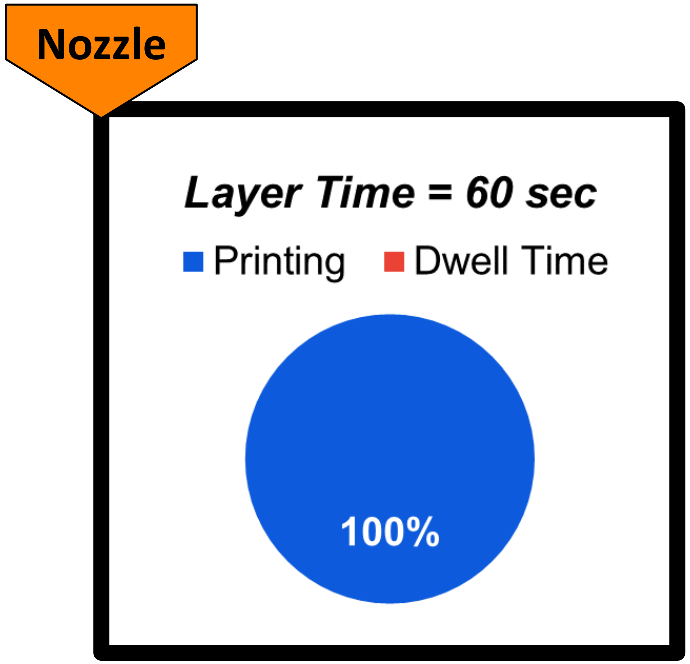
- Mechanical testing samples were taken from most center of each bead in the XZ Walls
- This significantly reduced influence of aligned fiber on testing
- This location was consistent across each sample during machining



Sampling technique shown here

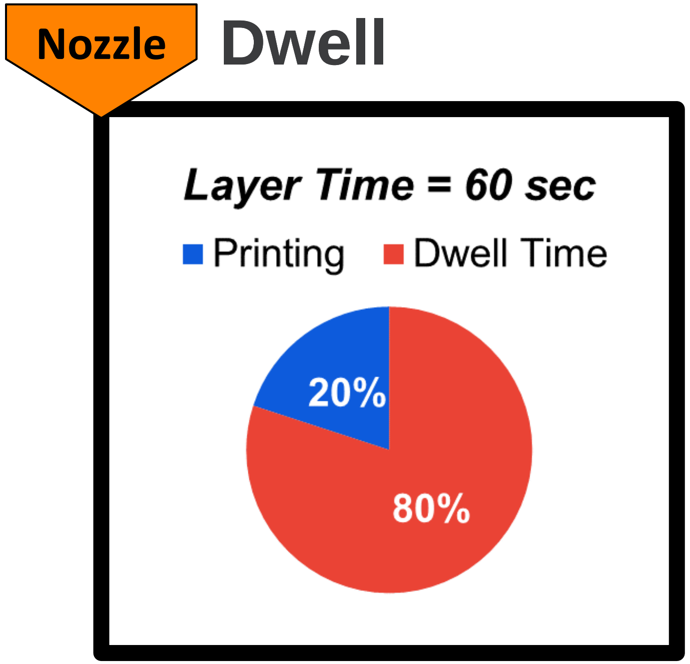
Different Print Control

Continuous Print



Printing each layer without interruption at a lower velocity

Paused Print



Simulates printing larger part with faster speeds needed to complete layer

Print Parameters

Print Parameters: Continuous				
Sample	**Specimen**	**Bead Width (mm)**	**Layer Time (sec)**	**Velocity (mm/s)**
1	1S	7.46	60	20
	1M	10.86	60	20
	1L	14.16	60	20
2	2S	7.50	120	10
	2M	12.13	120	10
	2L	14.44	120	10
3	3M1	10.00	240	5
	3M2	9.92	240	5
	3L	14.66	240	5

Print Parameters: Paused				
Sample	**Specimen**	**Bead Width (mm)**	**Layer Time (sec)**	**Velocity (mm/s)**
4	4S	7.06	60	100
	4M	10.32	60	100
	4L	13.76	60	100
5	5S	7.16	120	100
	5M	10.45	120	100
	5L	13.50	120	100
6	6S	7.24	240	100
	6M	10.41	240	100
	6L	13.39	240	100

- Bead width, layer time, and print velocity were changed with each print control
- Faster print velocity in the paused print → dwell time was introduced to meet desired layer time
- S, M, & L will signify small, medium & large beads within each sample group

Print Parameters

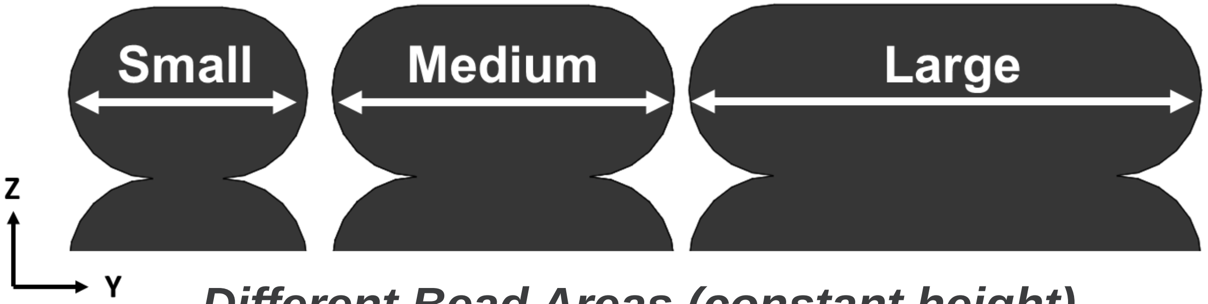
Print Parameters: Continuous			
Sample	**Specimen**	**Flow Rate (mm^3/s)**	**Shear Rate (s^{-1})**
1	1S	746	8
	1M	1086	11
	1L	1416	14
2	2S	375	4
	2M	607	6
	2L	722	7
3	3M1	250	3
	3M2	248	3
	3L	367	4

Print Parameters: Paused			
Sample	**Specimen**	**Flow Rate (mm^3/s)**	**Shear Rate (s^{-1})**
4	4S	3530	36
	4M	5162	53
	4L	6882	70
5	5S	3578	36
	5M	5225	53
	5L	6750	69
6	6S	3620	37
	6M	5203	53
	6L	6697	68

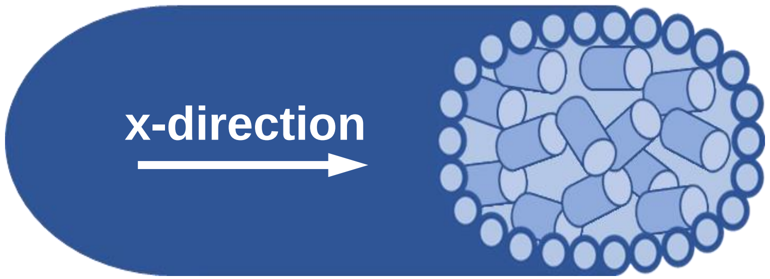
- Bead width, layer time, and print velocity were changed with each print control
- Faster print velocity in the paused print → dwell time was introduced to meet desired layer time
- S, M, & L will signify small, medium & large beads within each sample group

Expectations

- CTE influenced by fiber alignment which is affected by shear
  - Shear → bead geometry determines ratio of aligned to unaligned fibers
- Stiffness affected by fiber alignment, but less so in the z-dir
- Bonding strength will be higher with faster layer time
  - Larger bead → greater thermal mass & longer to cool → better bonding



Different Bead Areas (constant height)



Aligned bead shell with random center

Expectations

- **CTE influenced by fiber alignment which is affected by shear**
  - **Shear → bead geometry determines ratio of aligned to unaligned fibers**
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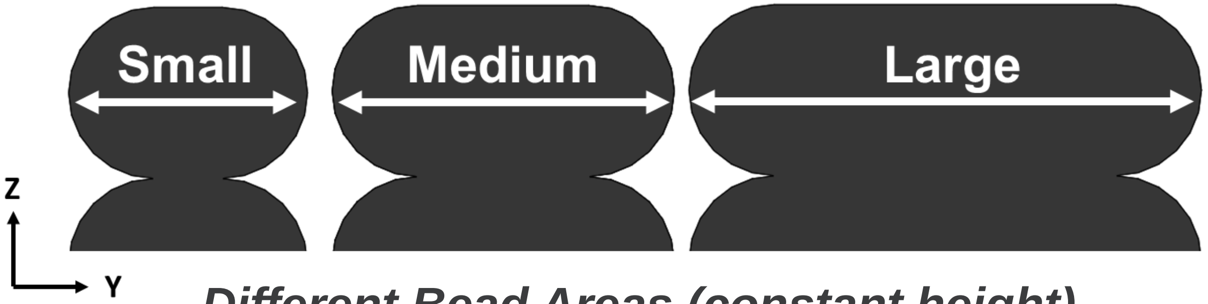

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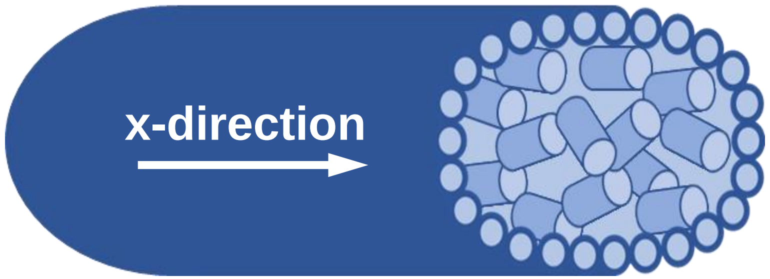
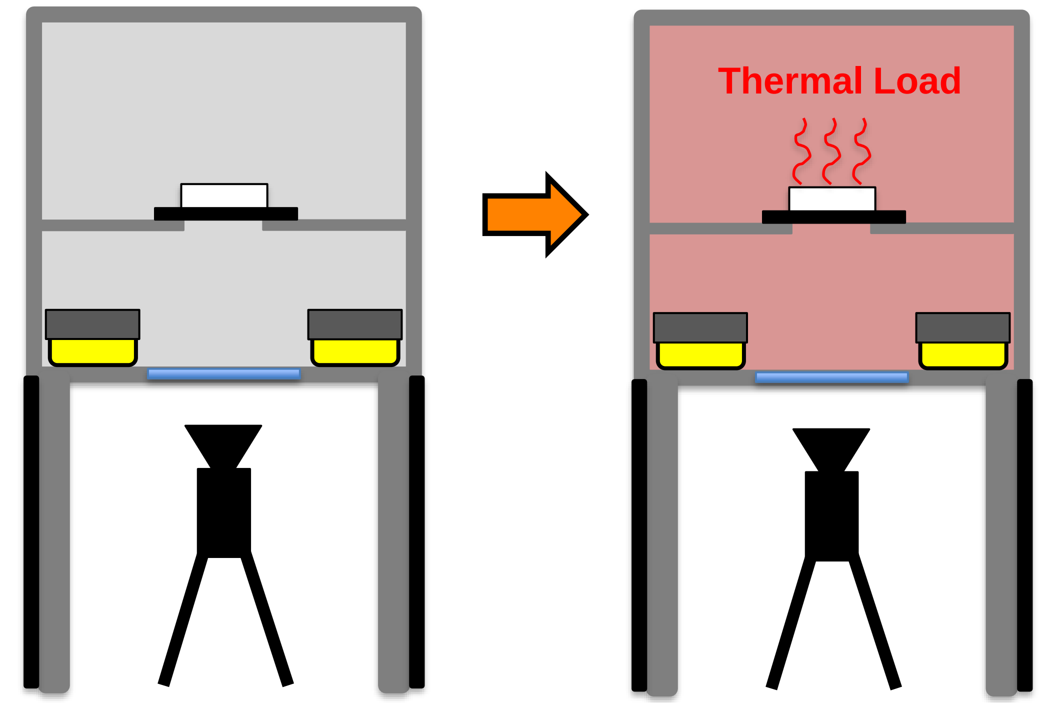


Aligned bead shell with random center

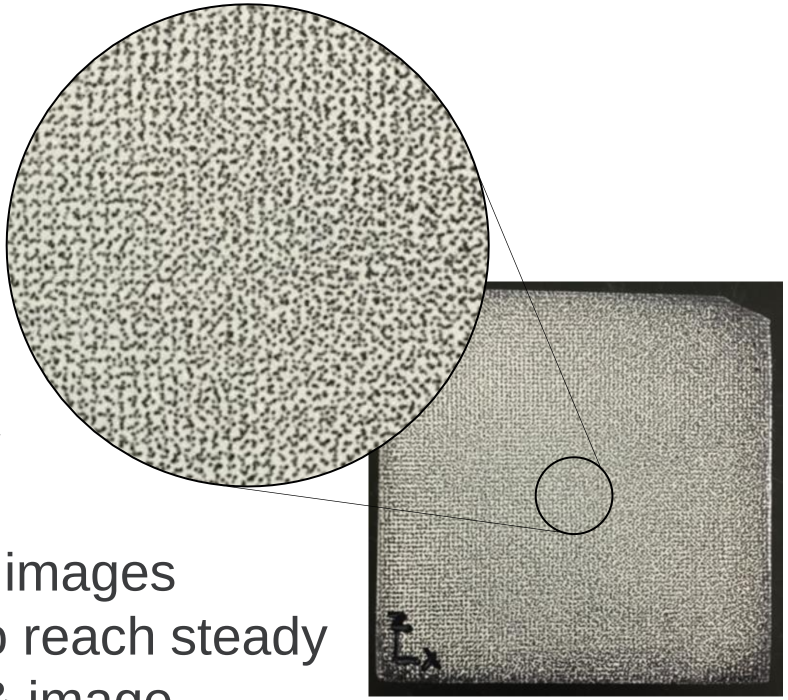
DIC Oven Procedure



Room Temperature **Steady State Temperature**

Procedure Overview

- Set sample
- Room temperature images
- Allow the sample to reach steady state temperature & image
- Upload images to Vic-2D
- Enter data in equation below to find CTE

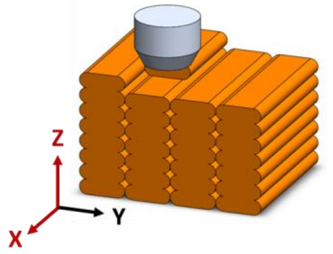


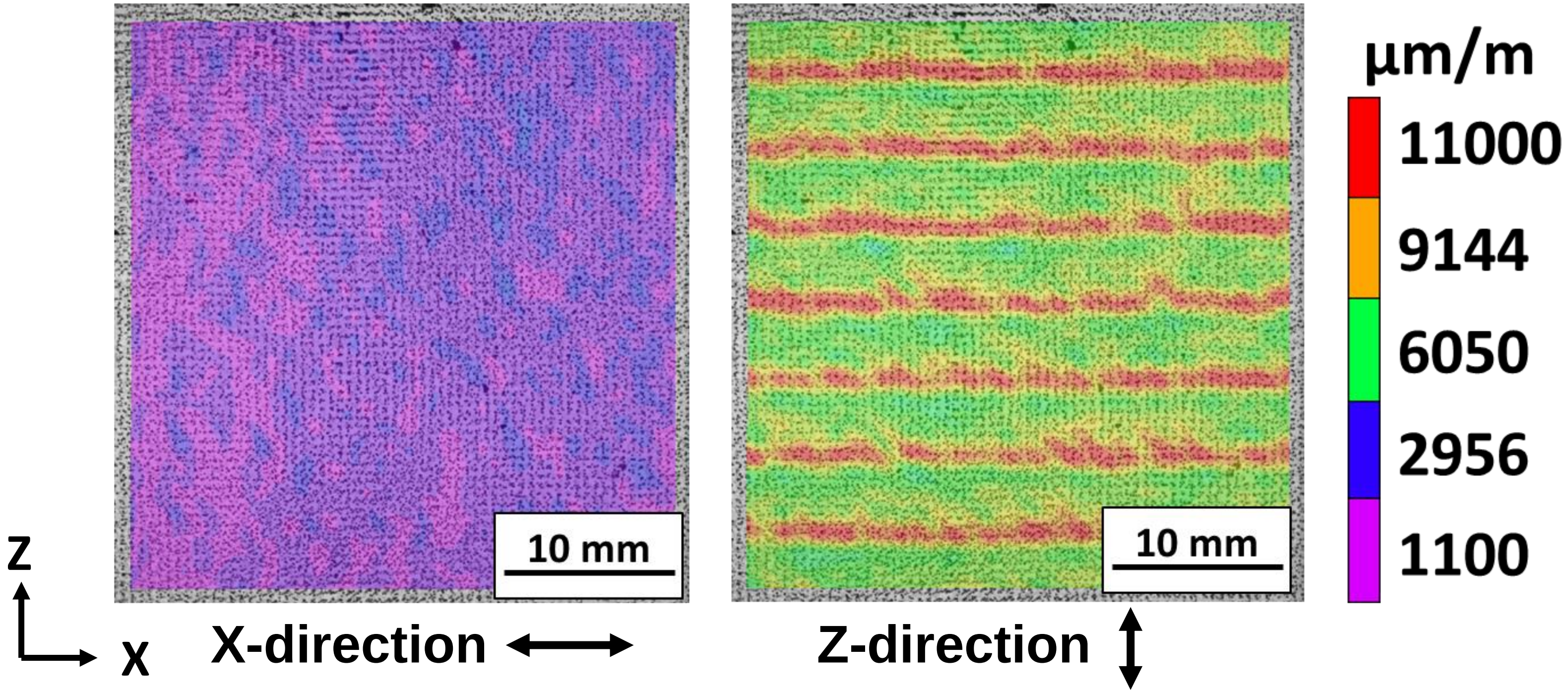
DIC Speckled Sample

$$CTE = \frac{\varepsilon_{SS} - \varepsilon_{RT}}{T_{SS} - T_{RT}}$$

ε = strain
T = temperature
SS = steady state temperature
RT = room temperature

Strain Plot

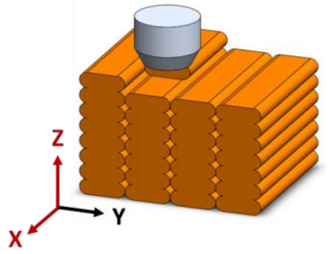


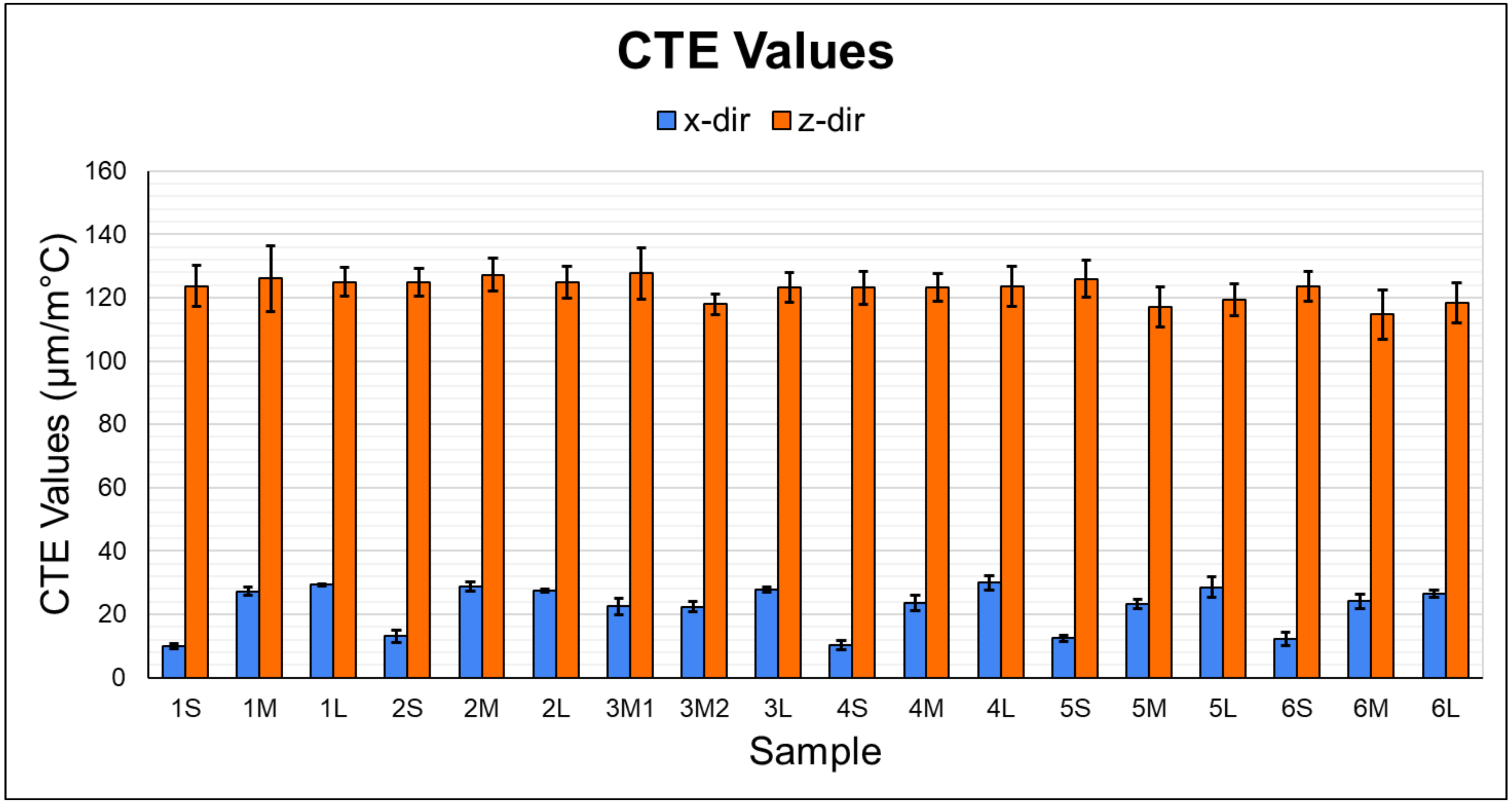


These strain plots help relate sample properties to the sample structure

- Stead state temperature
- Plots made using Vic-2D
- Homogenous low strain across the x-dir
  - Aligned fiber providing resistance
- Highest strain between print layers in the z-dir
  - Fibers randomly oriented in center of bead, aligned at edges

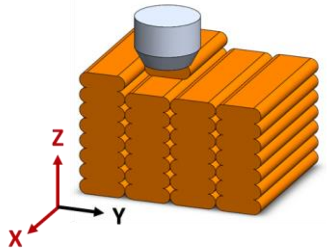
CTE Results

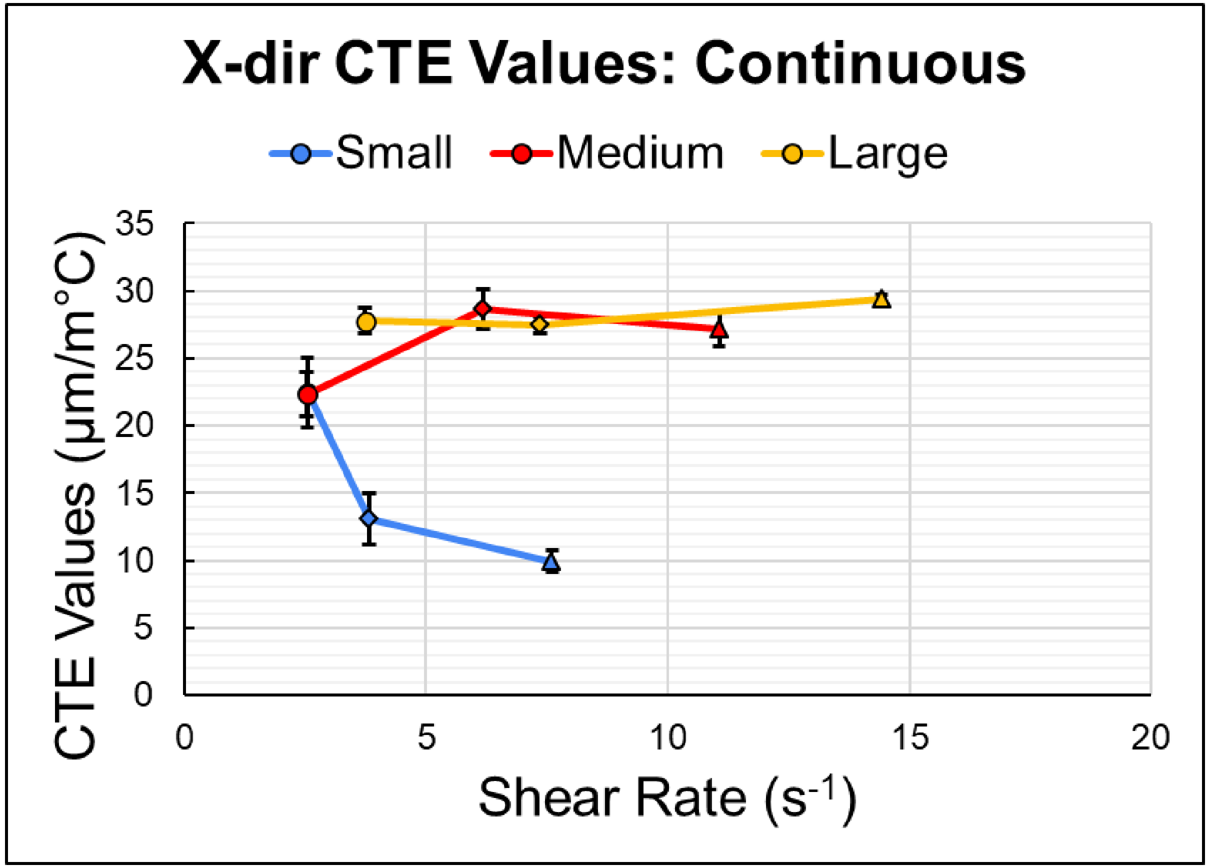




- Measured using DIC Oven
- **Overall trend of x-dir < z-dir**
- Expected from fiber alignment
- Effects captured by DIC strain plot

CTE Results: Continuous, x-dir

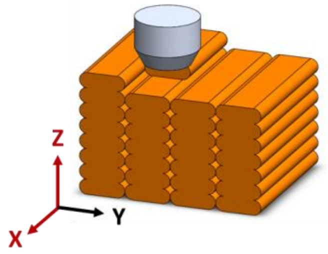


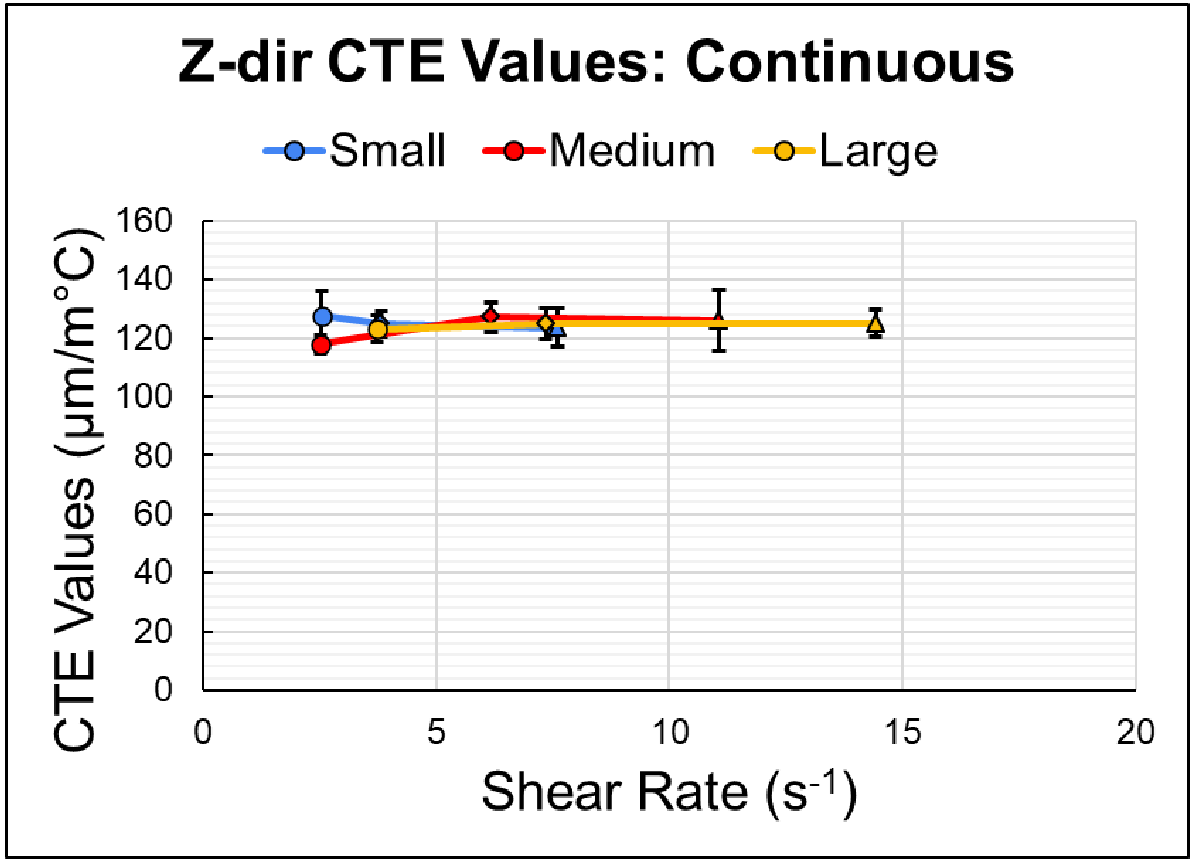


Here: ▲= 20 mm/s, ♦ = 10 mm/s, & ●= 5 mm/s

- Small bead CTE decreased with increased shear rate
  - Increased shear → more alignment & lower CTE
- Large bead relatively unaffected by increased shear rate
  - Thinnest shell of alignment relative to randomly oriented fiber

CTE Results: Continuous, z-dir

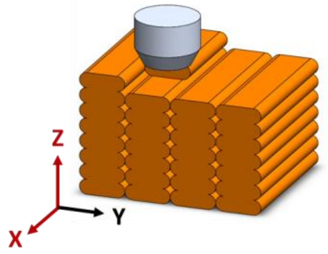


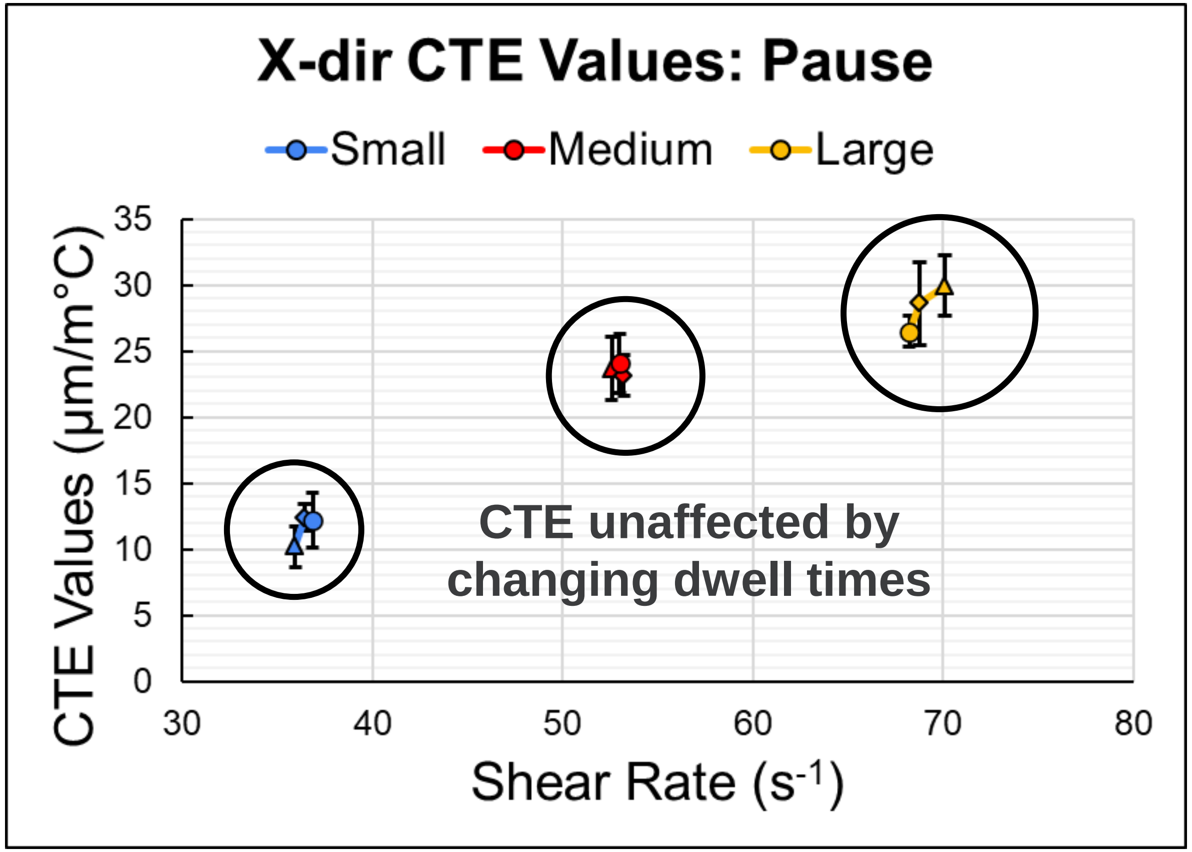


Here: ●= 5 mm/s, ♦ = 10 mm/s, & ▲= 20 mm/s

- Z-dir CTE relatively unaffected by the increasing shear alignment
  - All values ± 10 units of one another
- High CTE from little resistance provided by fiber in transverse direction
  - Evident from earlier strain plot

CTE Results: Pause, x-dir





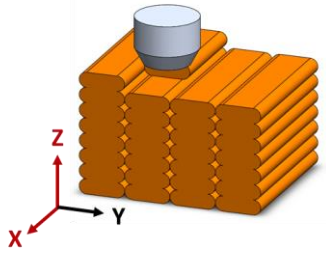
Here: ● = 48, ♦ = 108, & ▲ = 228 second dwell times

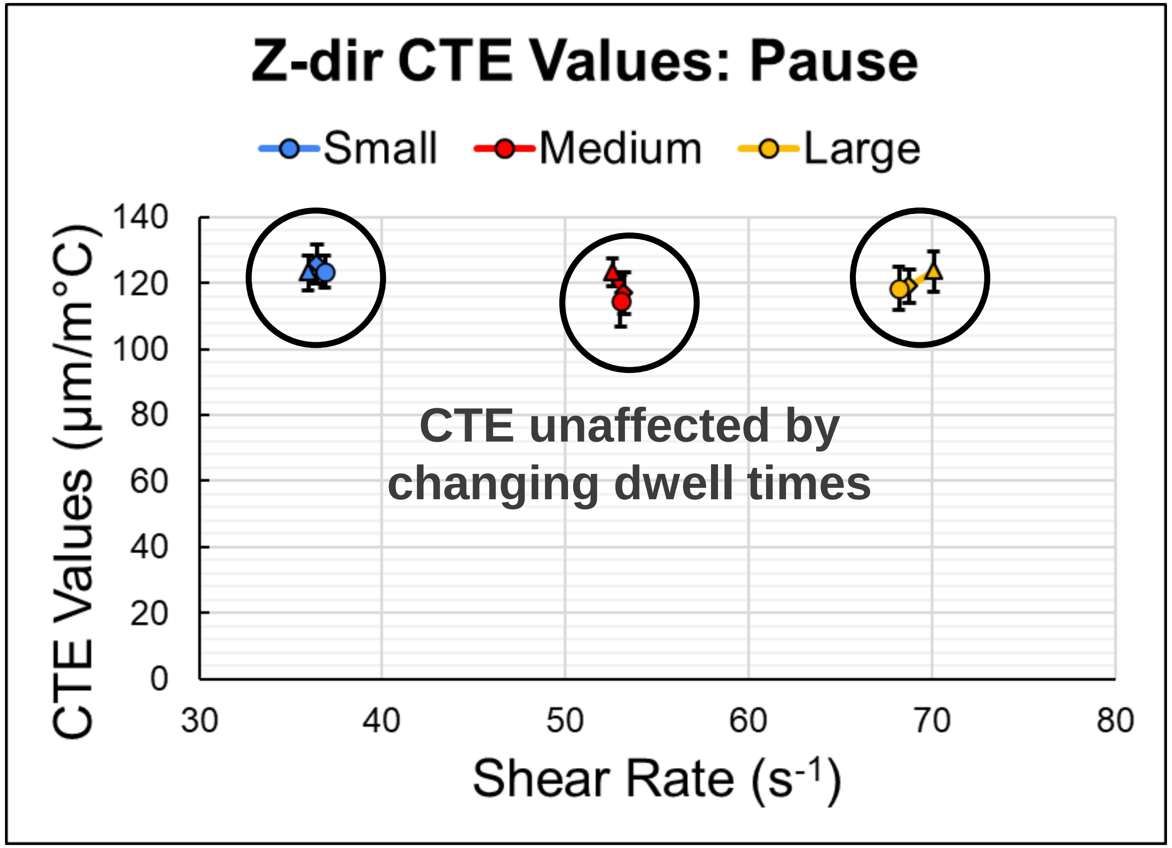
- Bead geometry, derives the x-dir CTE values → Smaller the bead, more aligned fiber, lower CTE
- Dwell time does not change fiber orientation
- Therefore, dwell time does not affect CTE

Oak Ridge National Laboratory

The University of Tennessee Knoxville

CTE Results: Pause, z-dir



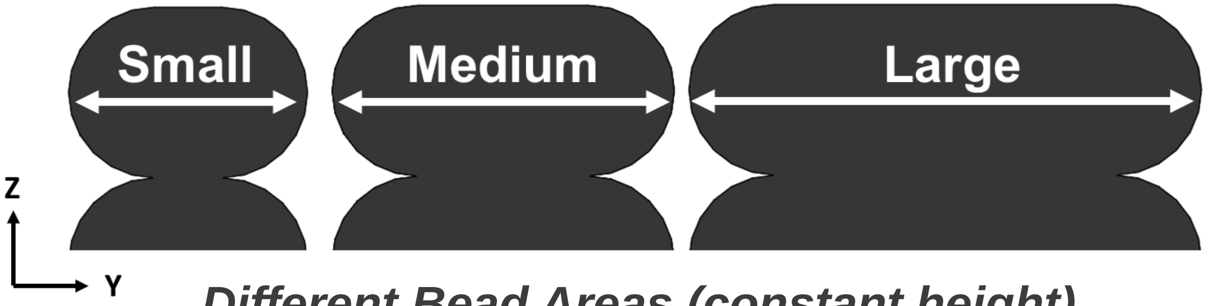


Here: ● = 48, ♦ = 108, & ▲ = 228 second dwell times

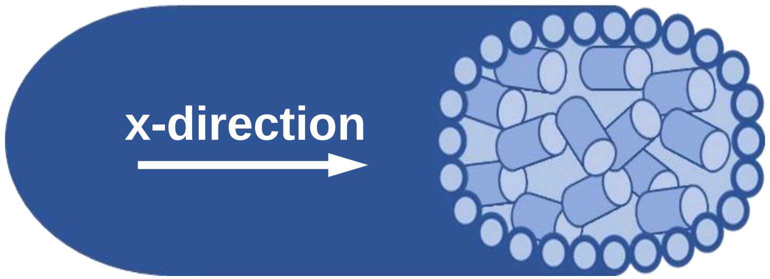
- Z-dir CTE unaffected by increasing shear rate
  - Fiber aligned layer edges provides little resistance in z-dir
- CTE unaffected by dwell
  - Dwell time does not change fiber orientation → CTE unaffected

Expectations

- ✓ CTE influenced by fiber alignment which is affected by shear
  - ✓ Shear → bead geometry determines ratio of aligned to unaligned fibers
- **Stiffness affected by fiber alignment, but less so in the z-dir**
- Bonding strength will be higher with faster layer time
  - Larger bead → greater thermal mass & longer to cool → better bonding



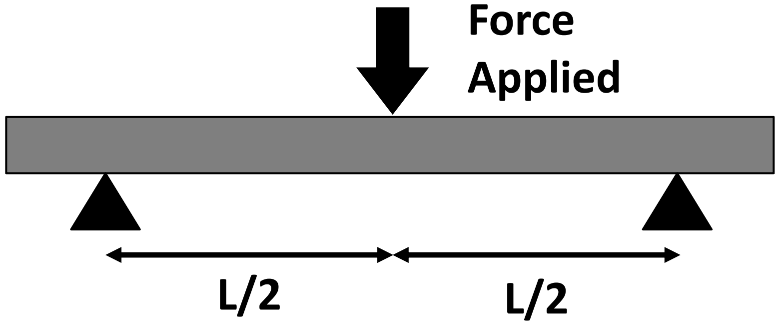
Different Bead Areas (constant height)

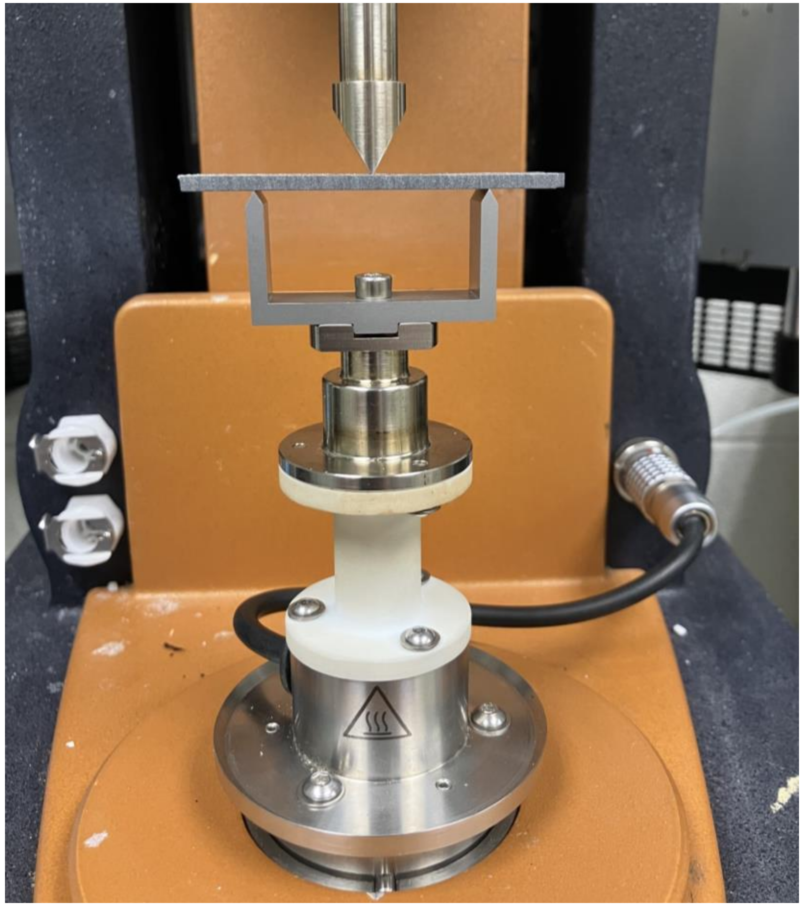


Aligned bead shell with random center

DMA Procedure

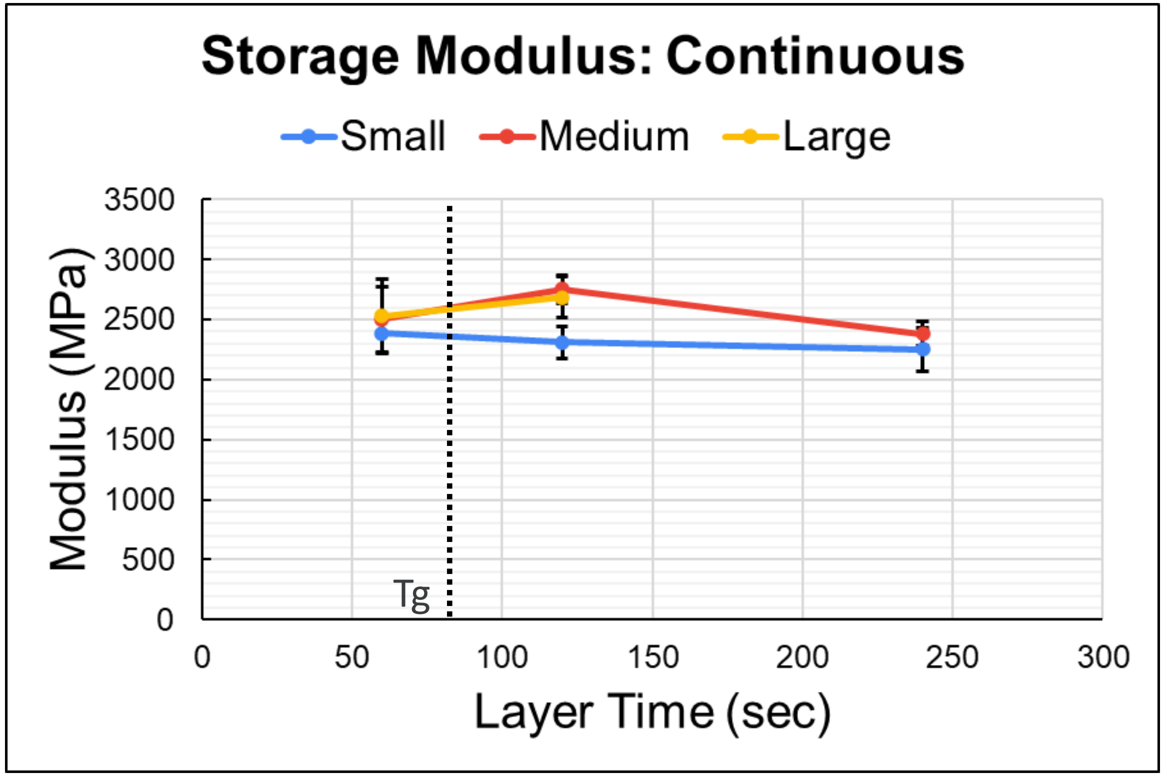
- TA Instruments Discovery Hybrid Rheometer (DHR)
- Tested for room temperature storage modulus data (stiffness)
- Sample dimensions: 64 x 13 x 3 mm
- Span length of 40 mm & frequency of 10Hz





DHR used for DMA Testing

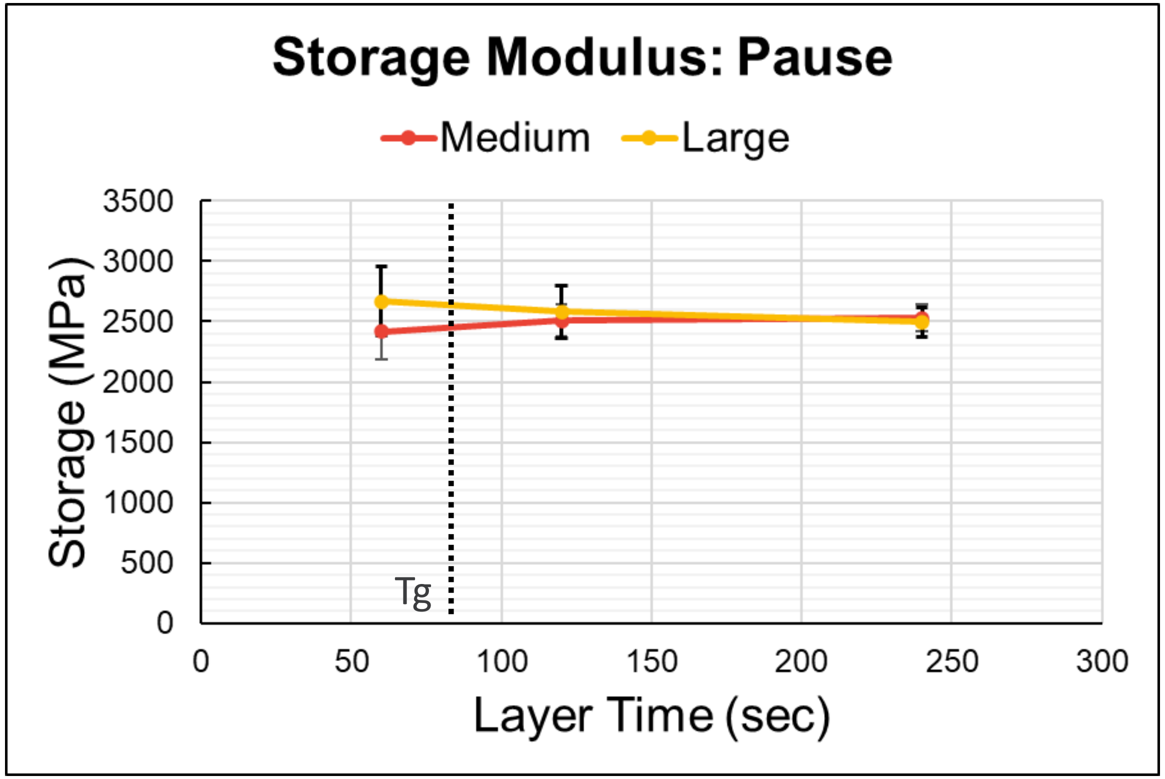
DMA Results: Continuous



** Note there was no data available for 3L **

- Continuous print shown plotted by **bead geometry**
- Tg represents time required to cool from extrusion to glass transition temperature
- Stiffness data relatively unaffected by layer time

DMA Results: Pause

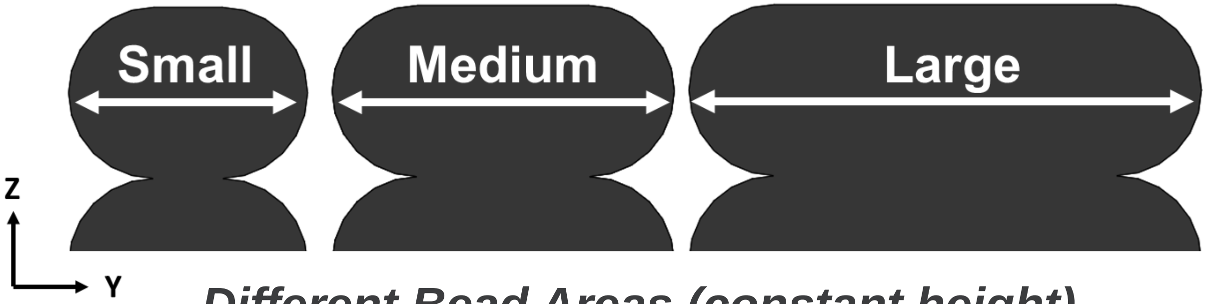


** Note there was no data available for 4S, 5S, or 6S **

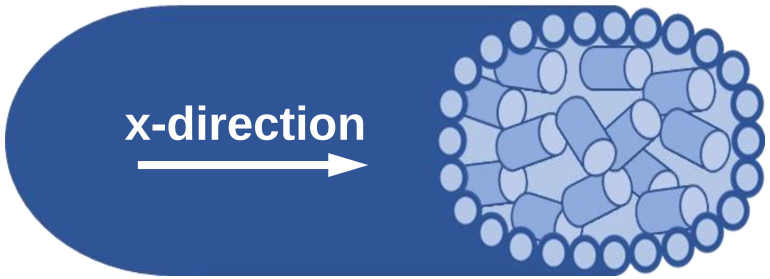
- Pause print shown plotted by **bead geometry**
- Tg represents time required to cool from extrusion to glass transition temperature
- Z-dir stiffness not significantly affected by layer time

Expectations

- ✓ CTE influenced by fiber alignment which is affected by shear
  - ✓ Shear → bead geometry determines ratio of aligned to unaligned fibers
- ✓ Stiffness affected by fiber alignment, but less so in the z-dir
- **Bonding strength will be higher with faster layer time**
  - **Larger bead → greater thermal mass & longer to cool → better bonding**



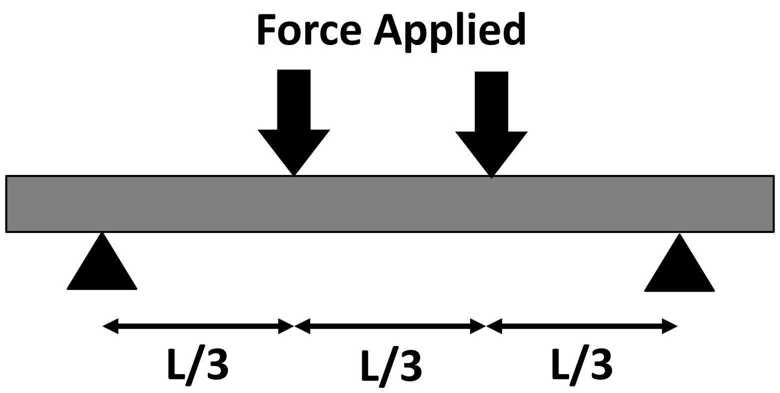
Different Bead Areas (constant height)

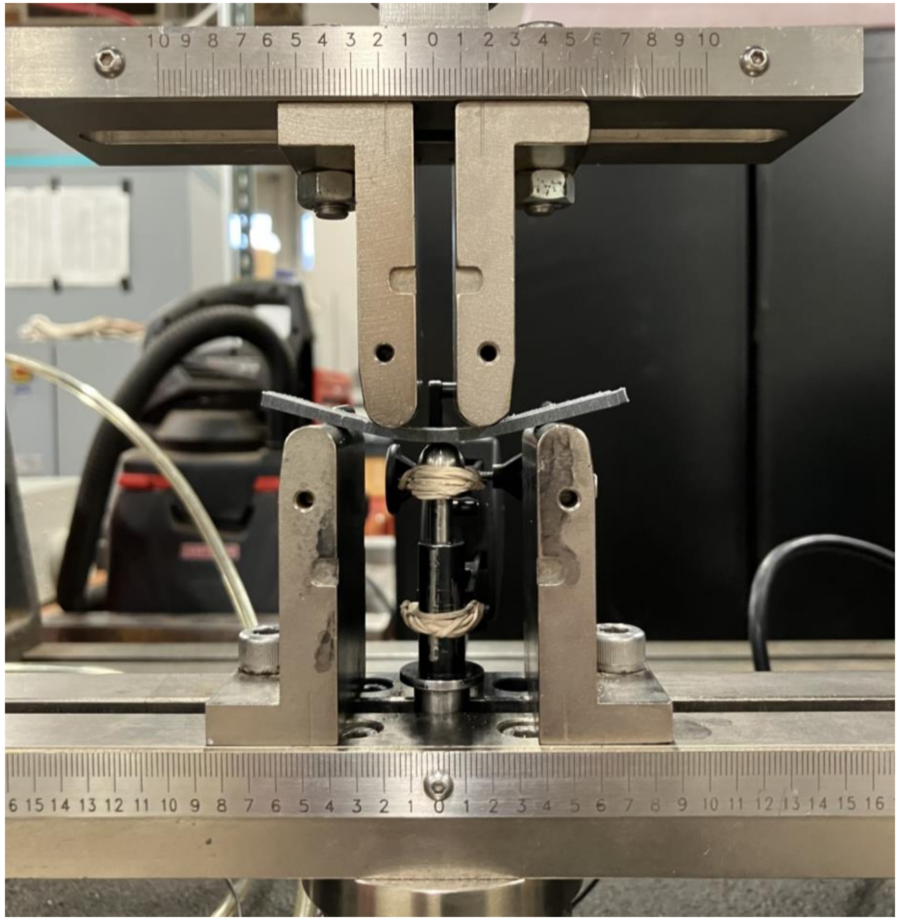


Aligned bead shell with random center

4pt Bend Procedure

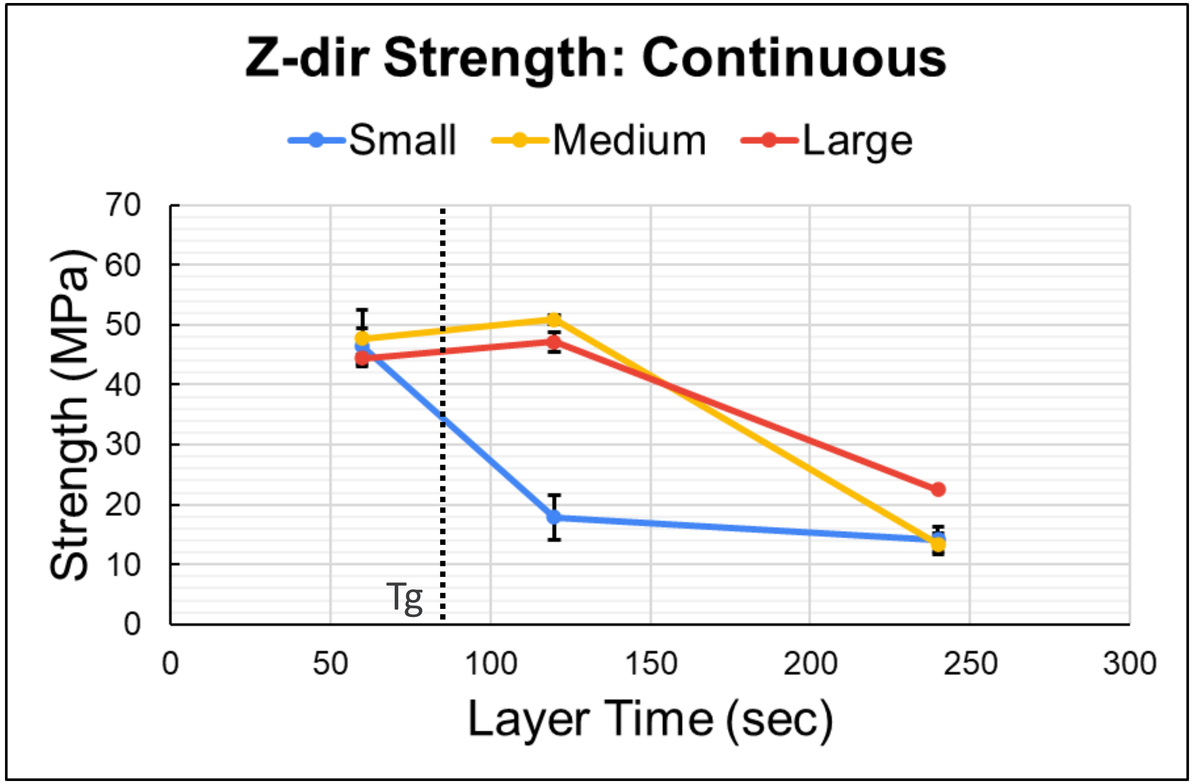
- Instron 5567 Frame with 30 kN load cell
- Testing z-dir strength to understand bond between layers
- Sample dimensions: 70 x 12.7 x 3 mm
- Span length was 48 mm with test speed of 1.42 mm/sec





Instron 5567 Frame

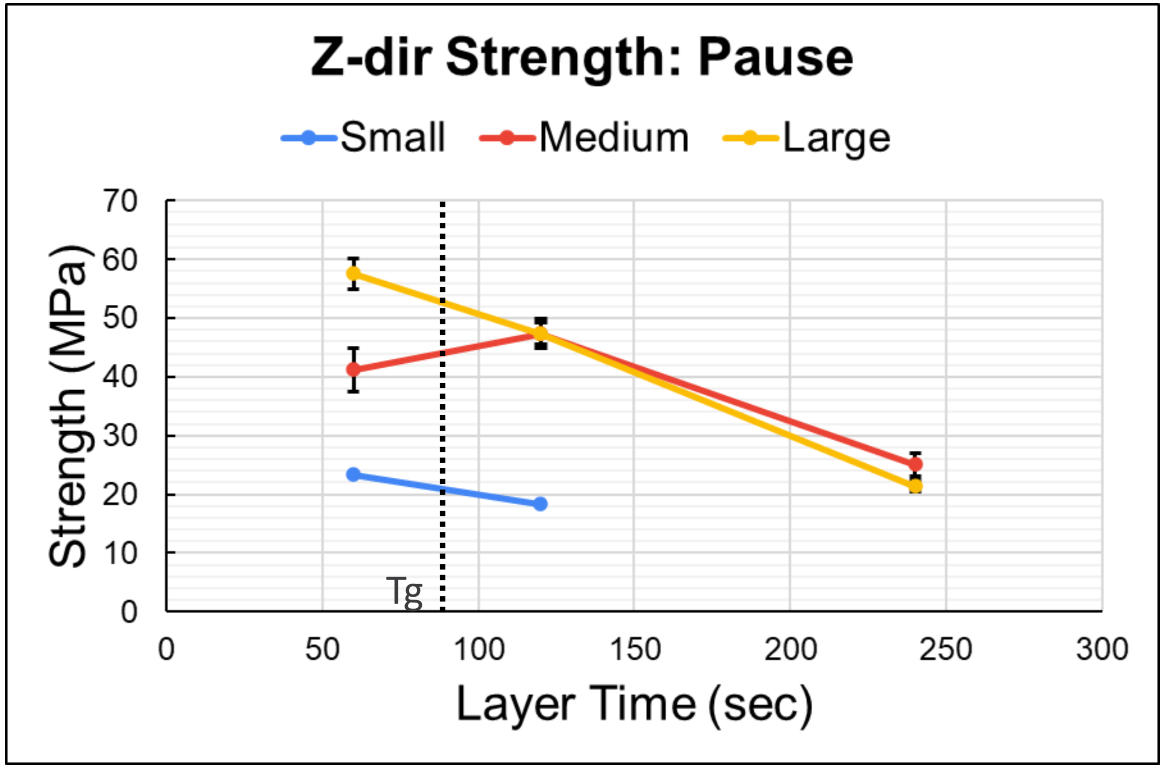
4pt Bend Results: Continuous



** Note there was no standard deviation data available for specimen3L **

- Continuous print plotted by **bead geometry**
- Tg represents time required to cool from extrusion to glass transition temperature
- Strongest layer bonding from fastest layer time (also before Tg line)
- Weakest layer bonding from 240 sec layer time
  - New bead deposited on a bead allowed too much time to cool resulting in weak bonding

4pt Bend Results: **Pause**

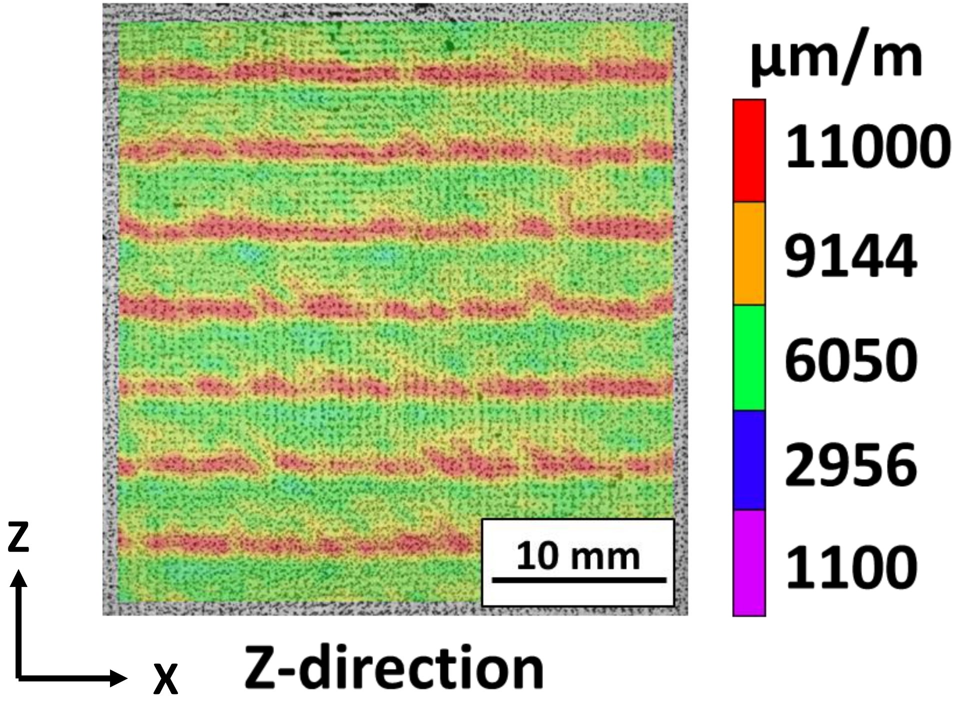


** Note there was no data available data for 6S and no standard deviation data available for specimen 4S or 5S**

- Pause print plotted by **bead geometry**
- Tg represents time required to cool from extrusion to glass transition temperature
- Overall drop in layer bonding once layer time exceeds time needed to reach Tg
- The 240 sec samples were again the weakest overall

Conclusions

- DIC Oven strain plots relate properties to structure
- Bead geometry drives x-dir CTE
- CTE unaffected by dwell time
- Stiffness was relatively unaffected from bead geometry & layer time
- Layer bonding was improved with faster layer times



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Thank you for your time!

Any Questions?

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