EFFECTS OF FIBER ALIGNMENT ON THE THERMOMECHANICAL PROPERTIES OF LARGE-FORMAT PRINTED COMPOSITE POLYMER STRUCTURES

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PCAM Polymer Composite Additive Manufacturing

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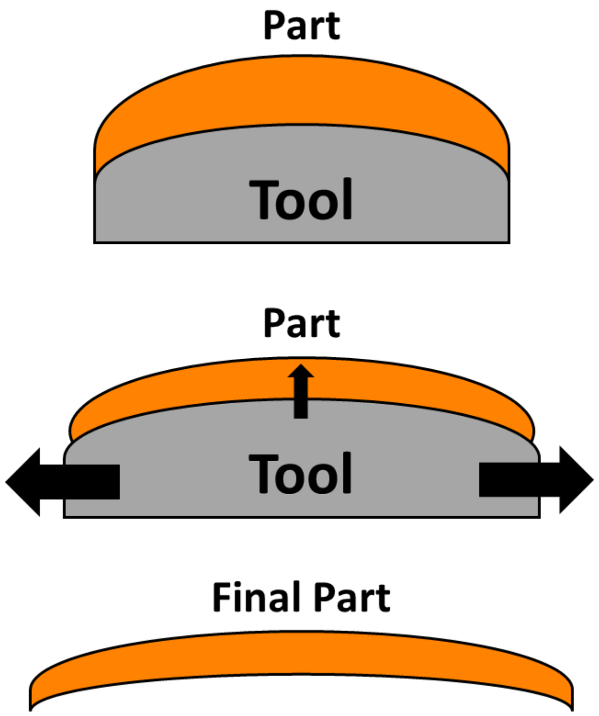
Overview Moving Forward

- Background
- Materials for Study
- Microscopy
- DIC Oven Testing
- CTE Modeling
- Conclusions

DIC Oven at the
University of Tennessee

Large-Format Additive Manufacturing

- Large-Format AM (LFAM) is advantageous for tooling applications[1]
- Big Area Additive Manufacturing (BAAM) and other LFAM type systems can create large complex parts
- Fiber Reinforced Polymers (FRP) feedstock increases part stiffness and lowers coefficient of thermal expansion (CTE)[2]
- AM tools may still experience warpage at autoclave conditions

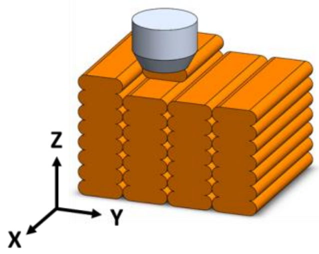


Tool warping due to anisotropic expansion

What leads to this warpage?

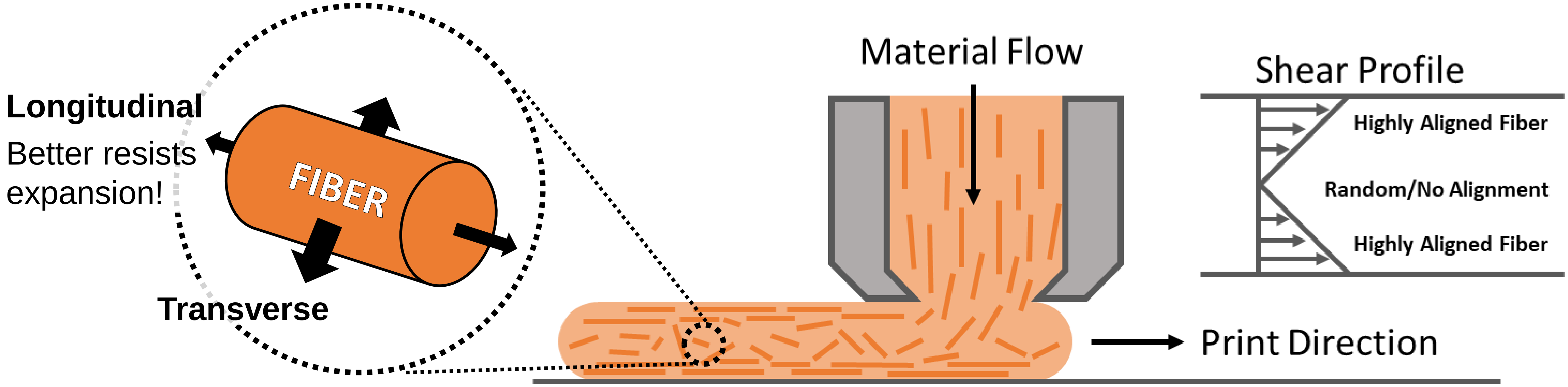
1. Duty et al., 2015, DOI: 10.2172/1209207
2. Love et al., 2014, DOI:10.1557/jmr.2014.212

Fiber Alignment



Fiber Reinforced Polymer Composites = MATRIX + FIBER

- During the extrusion, fibers are aligned by nozzle shear in the print direction[1]
- This results in highly aligned bead edge with a randomly oriented center by comparison[2]
- After extrusion, the fiber aligned bead has a highly anisotropic microstructure
- 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

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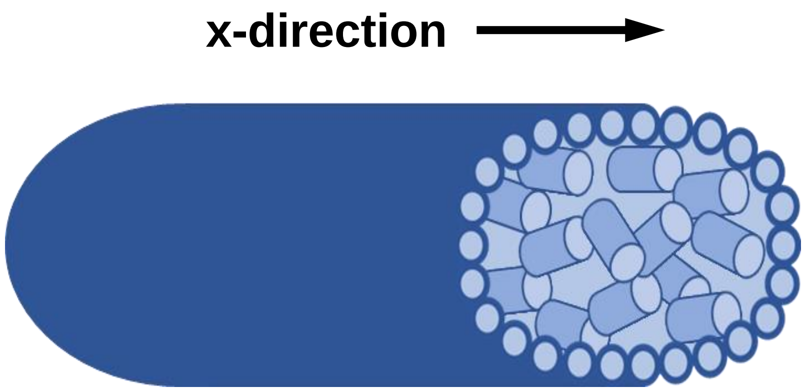
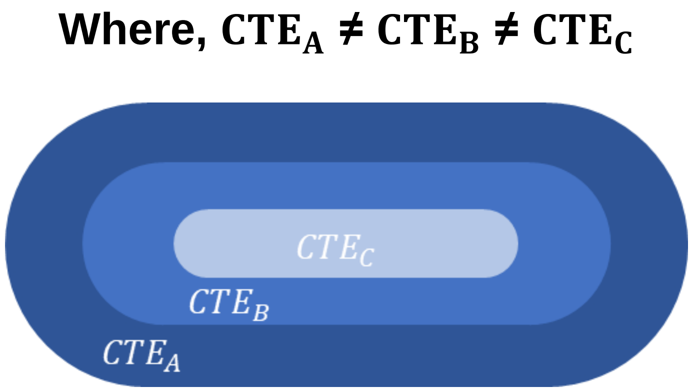
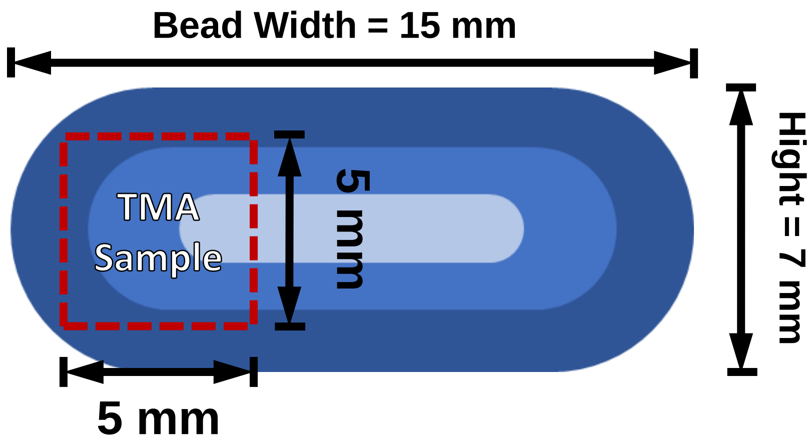
Anisotropy from Fiber Alignment

- 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]







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

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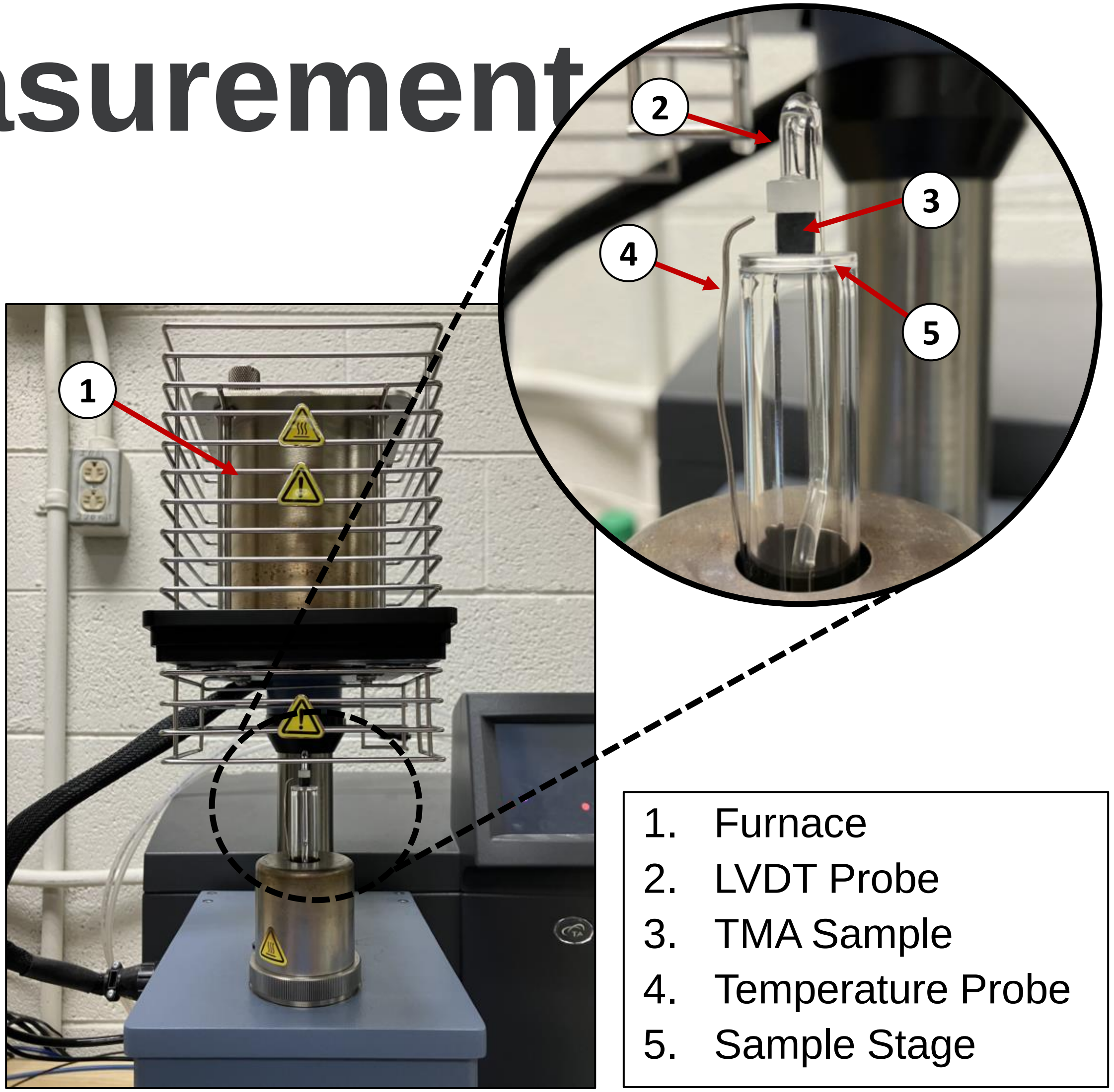
Traditional CTE Measurement

Thermomechanical Analysis (TMA)

- Traditionally used for CTE measurements
- TMA measures a small specimen (max size of 10 x 10 x 10 mm)[1]
- Assume sample represents entire part
- Correct assumptions for homogenous material → incorrect for anisotropic material



TMA measures a small specimen

- ➢ *Individual BAAM bead is typically wider than maximum TMA dimensions*

Assume sample represents entire part

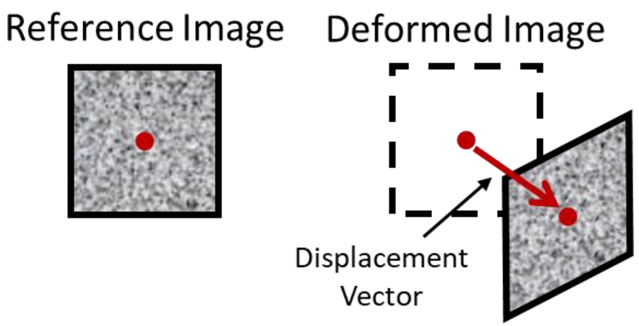
- ➢ *Different behavior at bead interfaces, center of the bead, across beads, and between layers*

1. ASTM E831, DOI: 10.1520/E0831-19

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

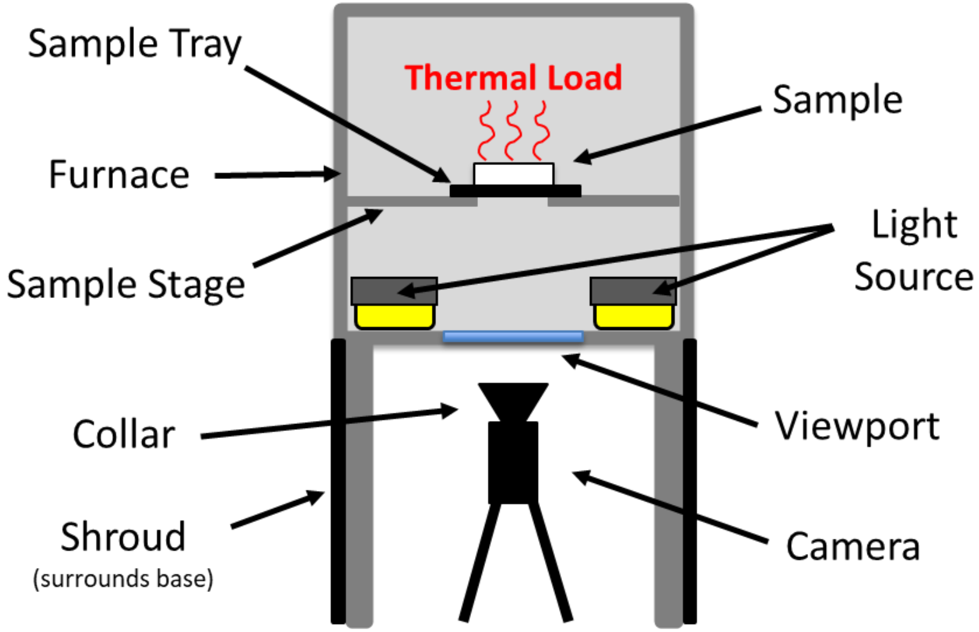
DIC Oven Overview

2D Digital Image Correlation

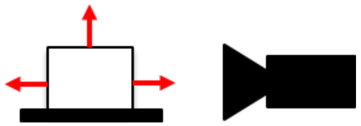


Digital Image Correlation (DIC) tracks the location of speckles from a reference to deformed state to create displacement vectors

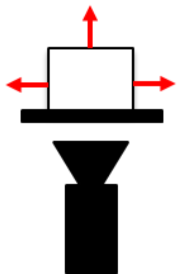
Major Components of the DIC Oven



Camera Placement

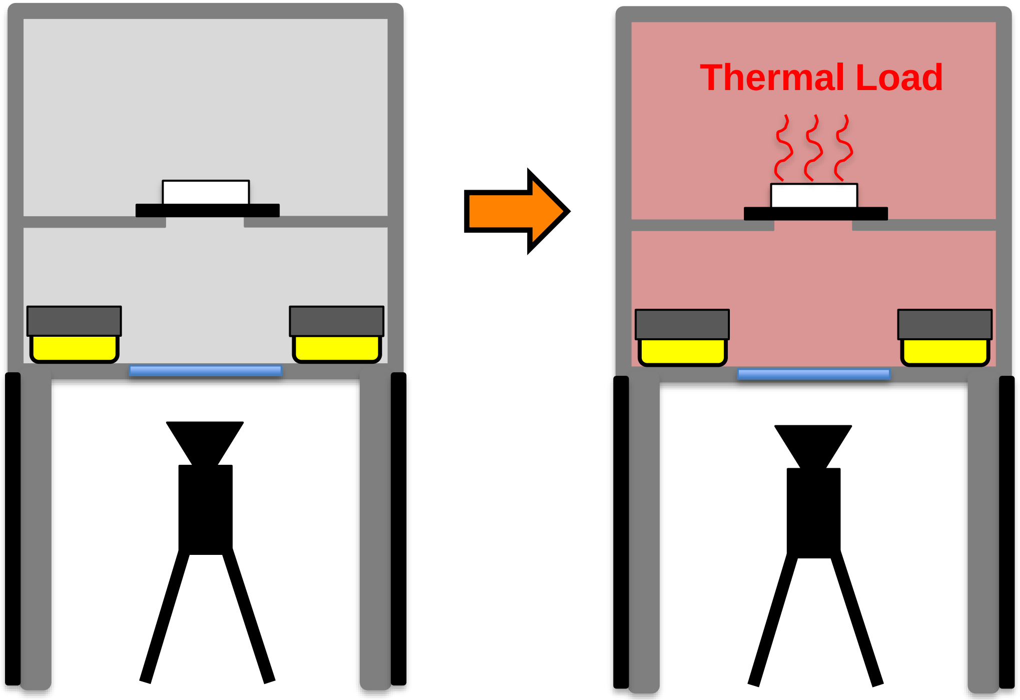


Typical 2D DIC camera placement can record expansion towards camera as false strain



DIC Oven camera placement greatly reduces chances of capturing false strain

DIC Oven Procedure



Room Temperature

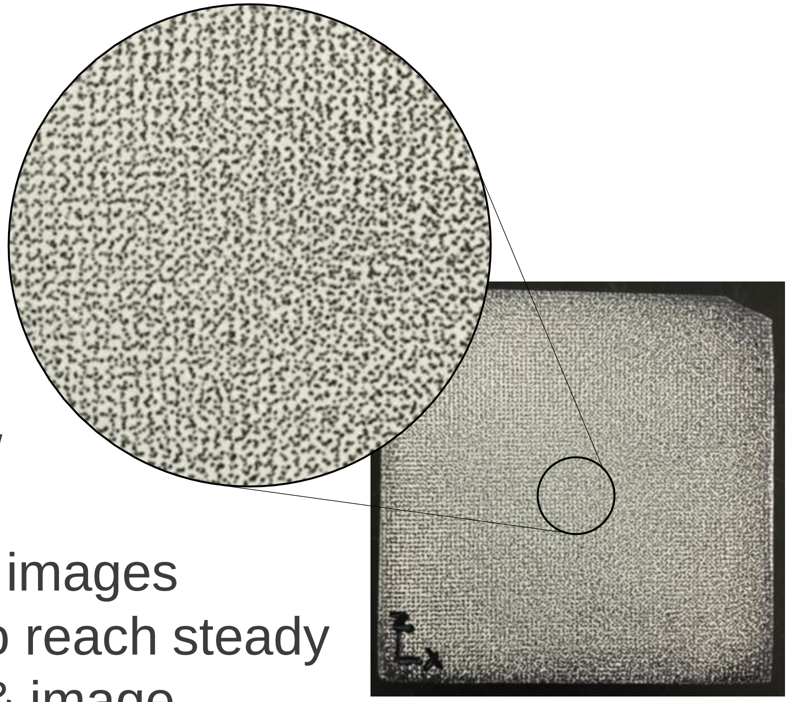
Steady State Temperature

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

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

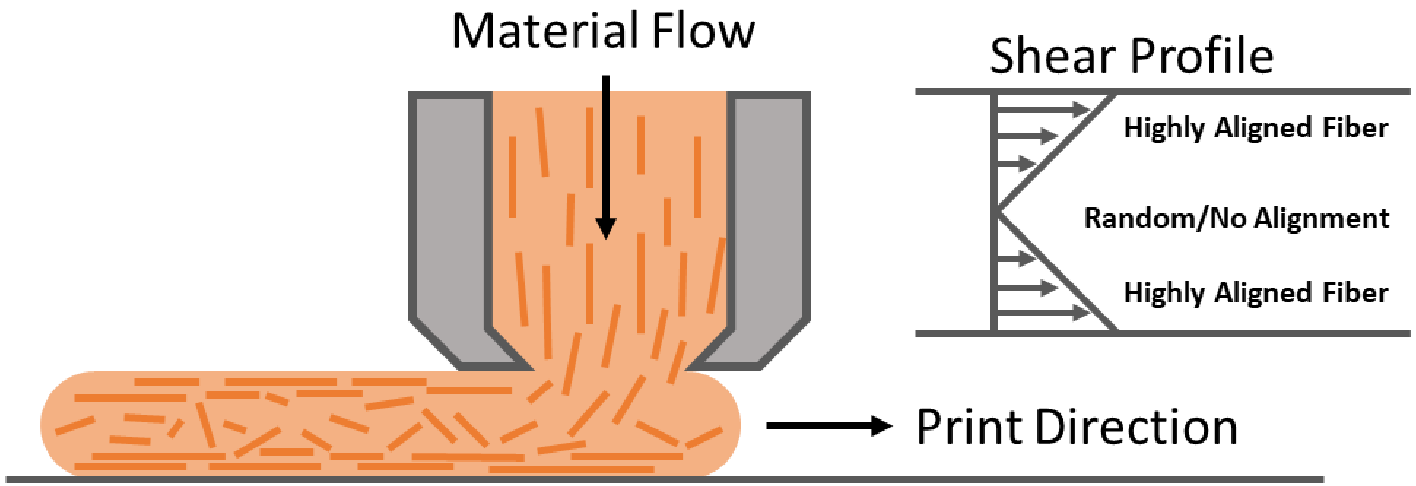
ε = strain
T = temperature
SS = steady state temperature
RT = room temperature



DIC Speckled Sample

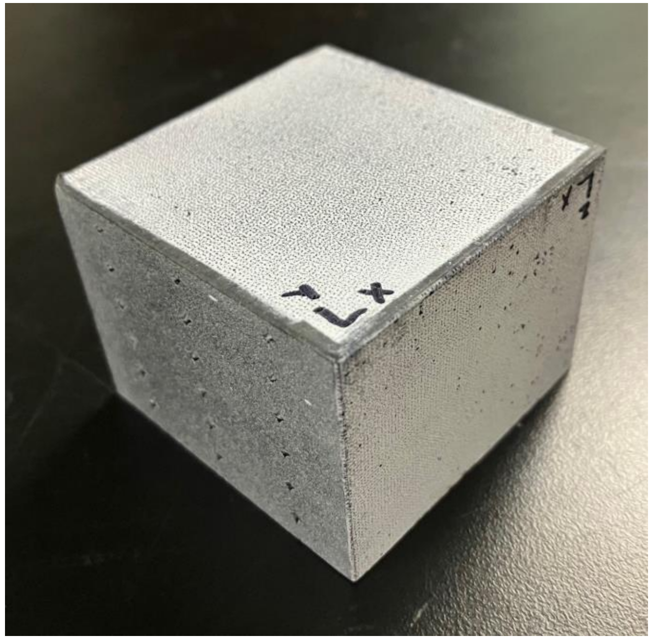
Objectives

- Relate fiber orientation to thermomechanical properties using optical methods and the DIC Oven
- Develop CTE model incorporating degree of fiber alignment to thermal expansion & validate with DIC Oven



Materials for Study

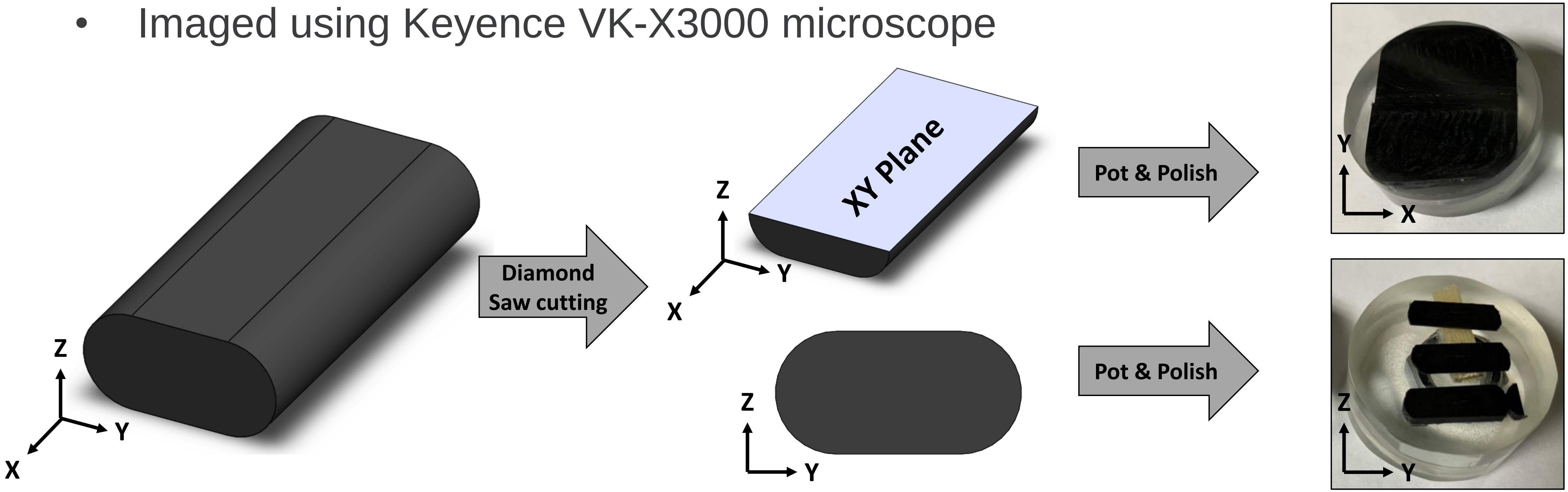
- 20% CF-ABS material printed using BAAM
- Microcopy samples machined to show XY and YZ planes for LFAM beads
- DIC cube (50 x 50 x 50 mm) machined to have flat, parallel faces and speckled



DIC sample speckled for 2D-DIC

Microscopy

- CF-ABS samples potted in Buhler EpoxiCure2 epoxy using a 1.25” puck
- Polished using an Allied High Tech MetPrep 3
- Imaged using Keyence VK-X3000 microscope



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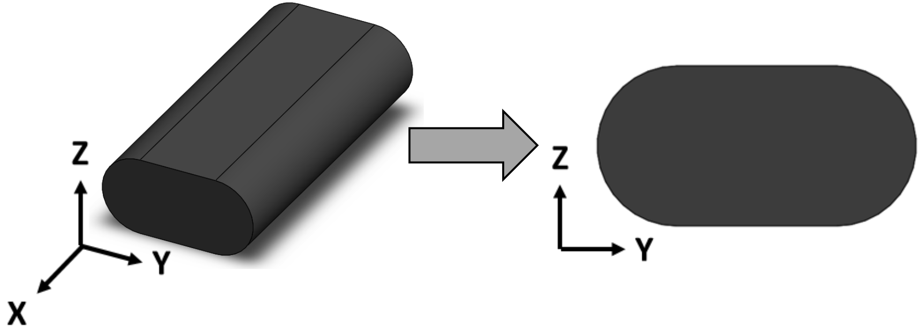
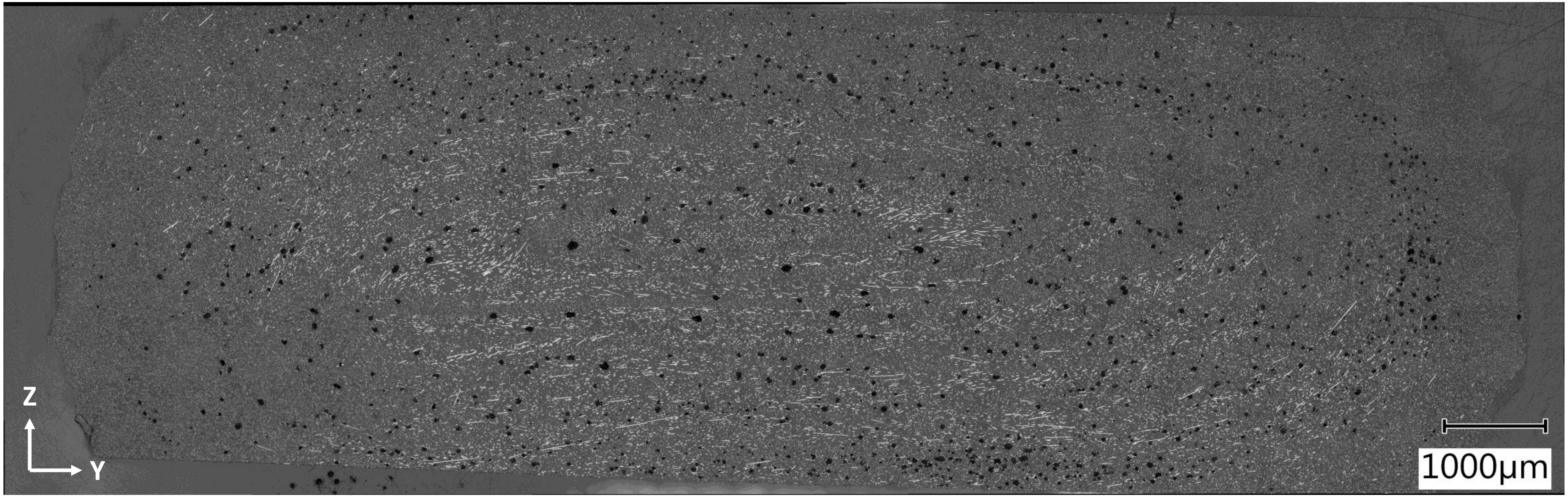
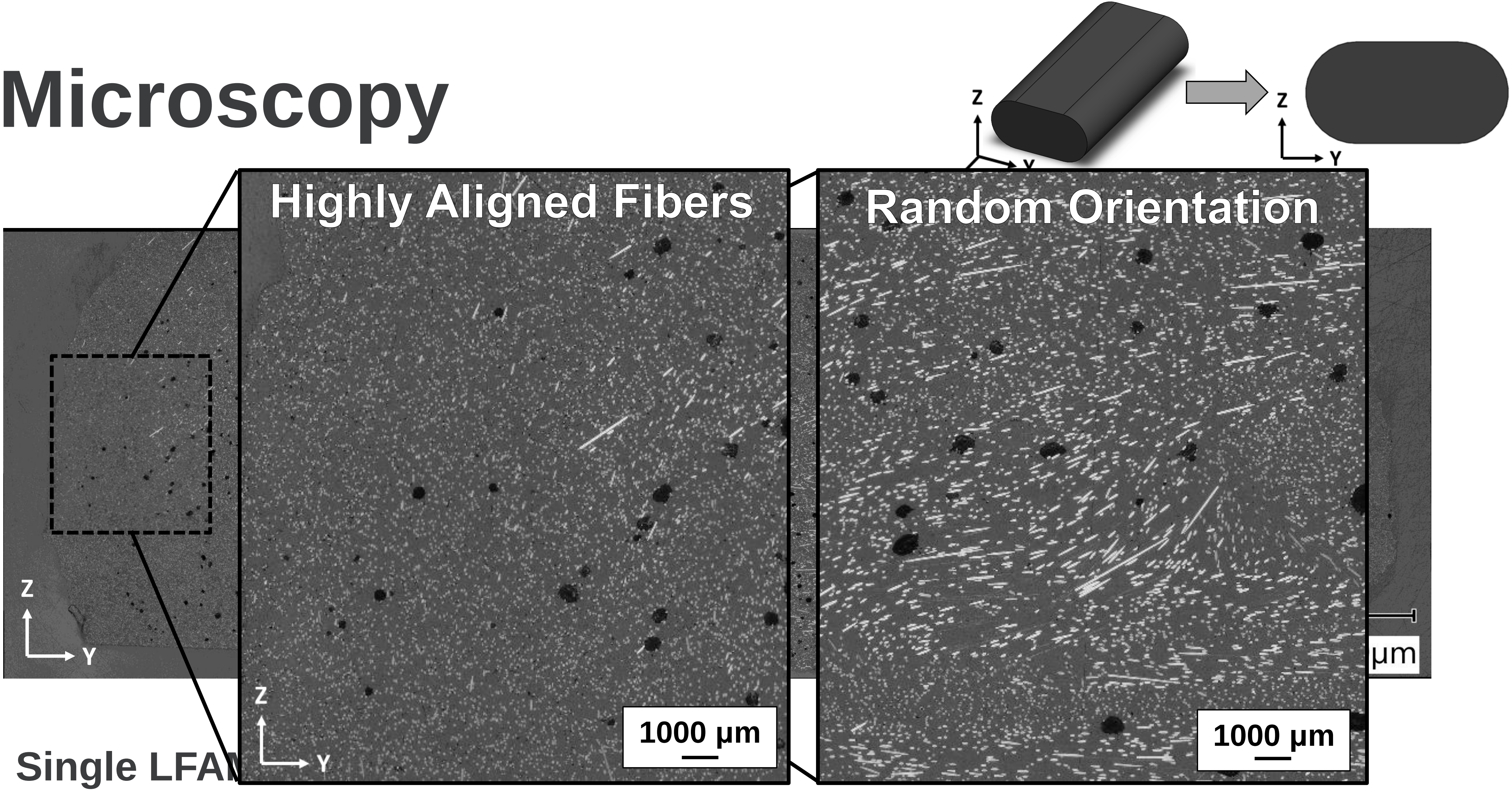
Microscopy





Single LFAM bead shown here

Microscopy



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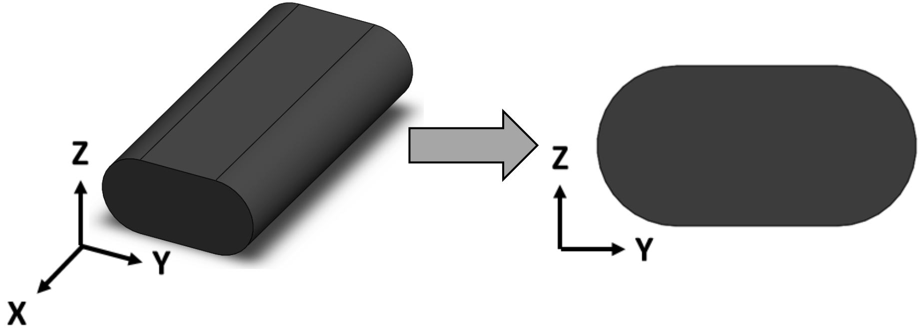
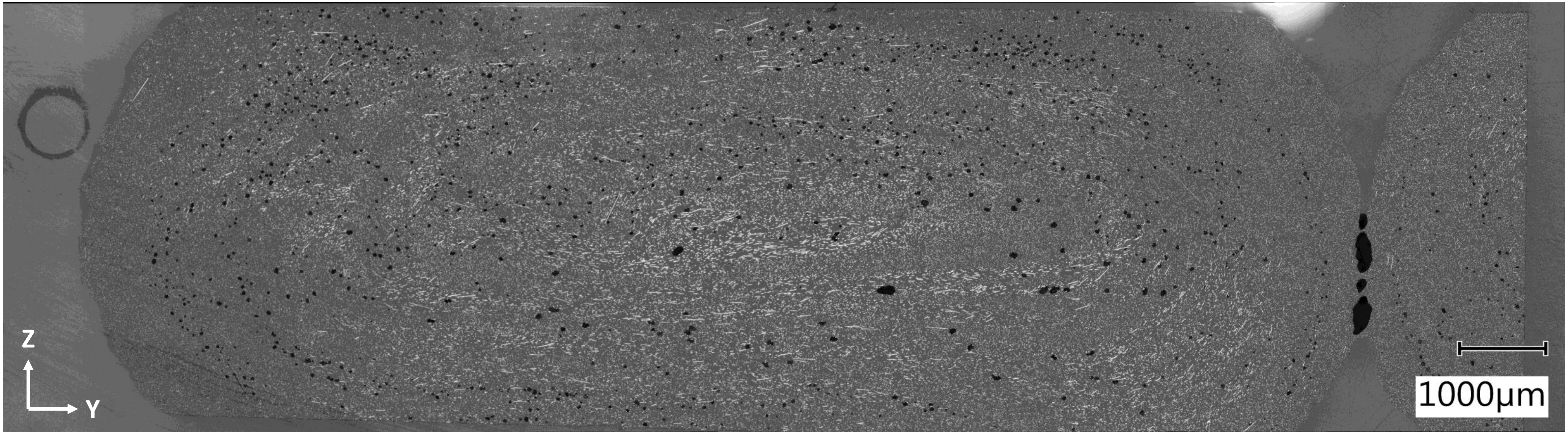
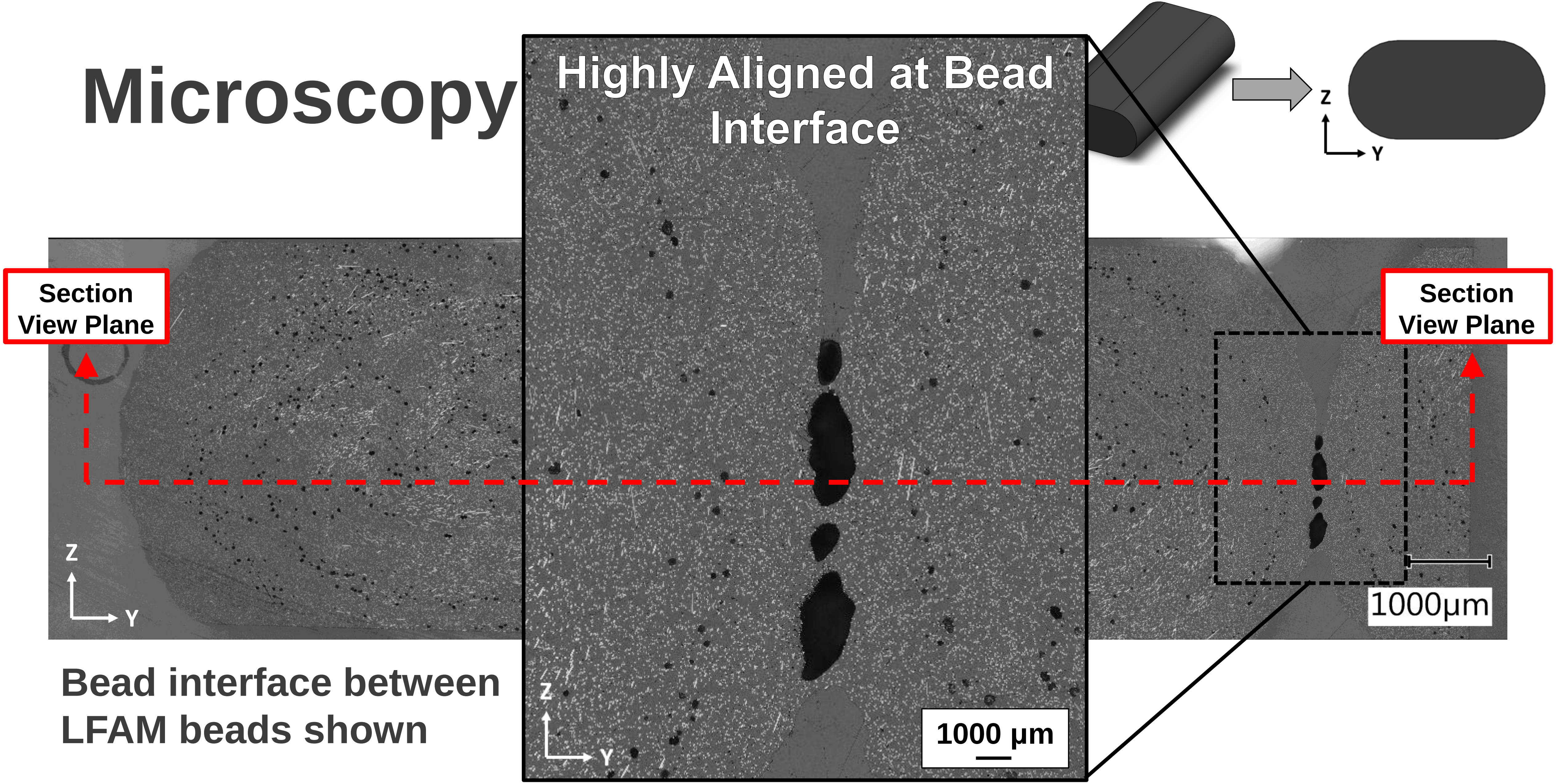
Microscopy





Bead interface between LFAM beads shown

Microscopy



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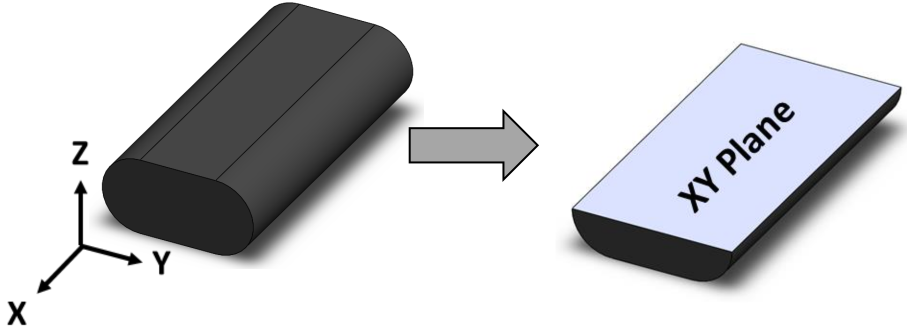
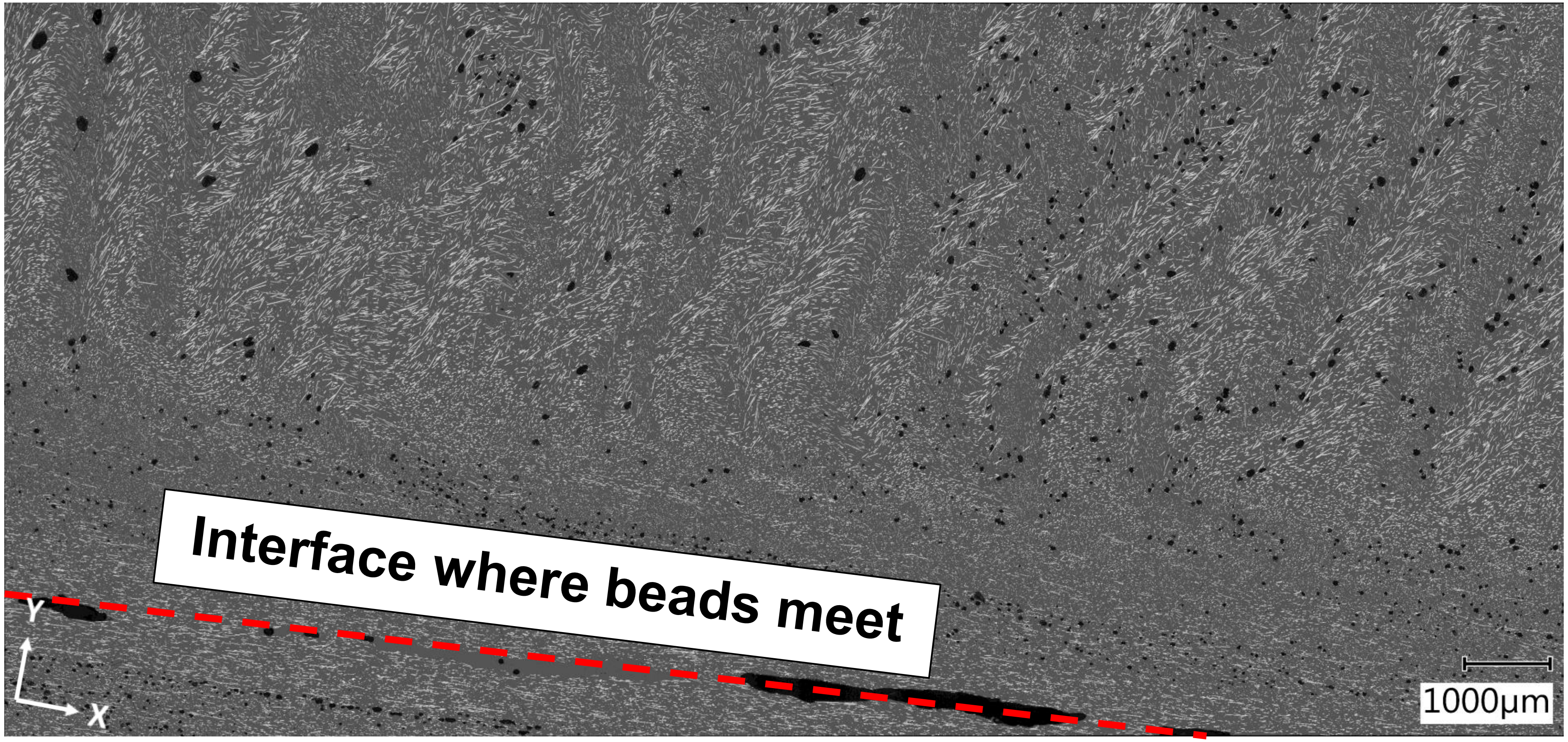
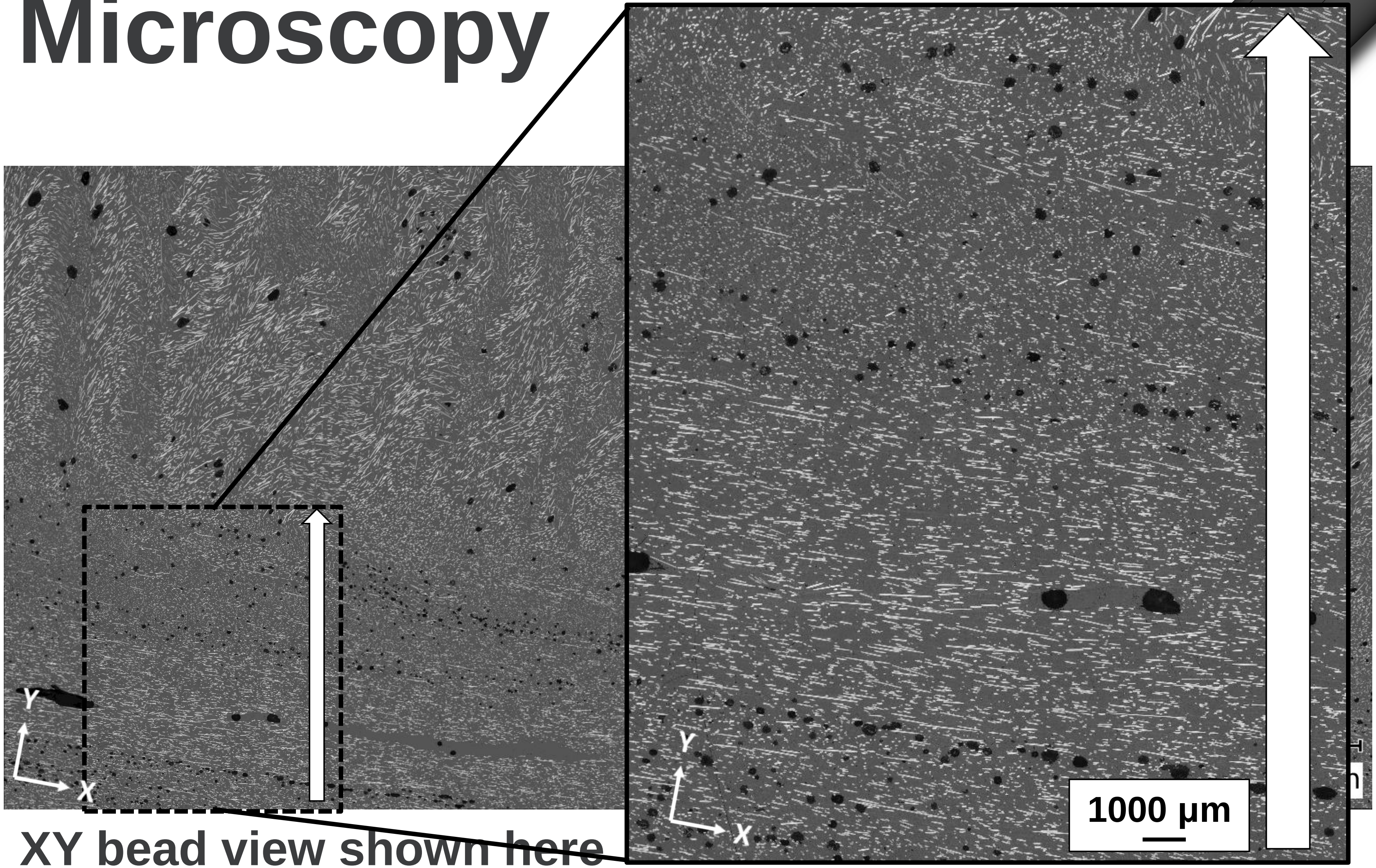
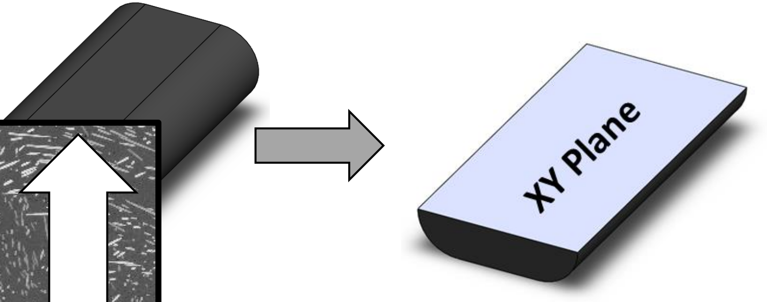




XY bead view shown here

Microscopy



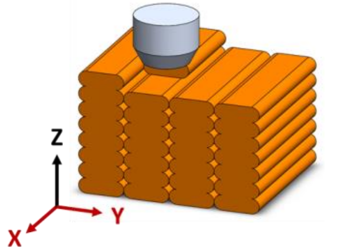


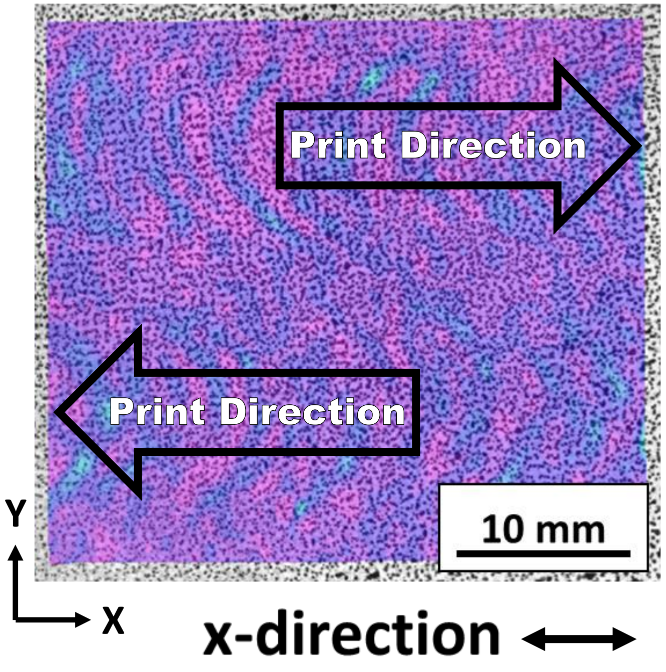
Notice how alignment decreases away from bead edge

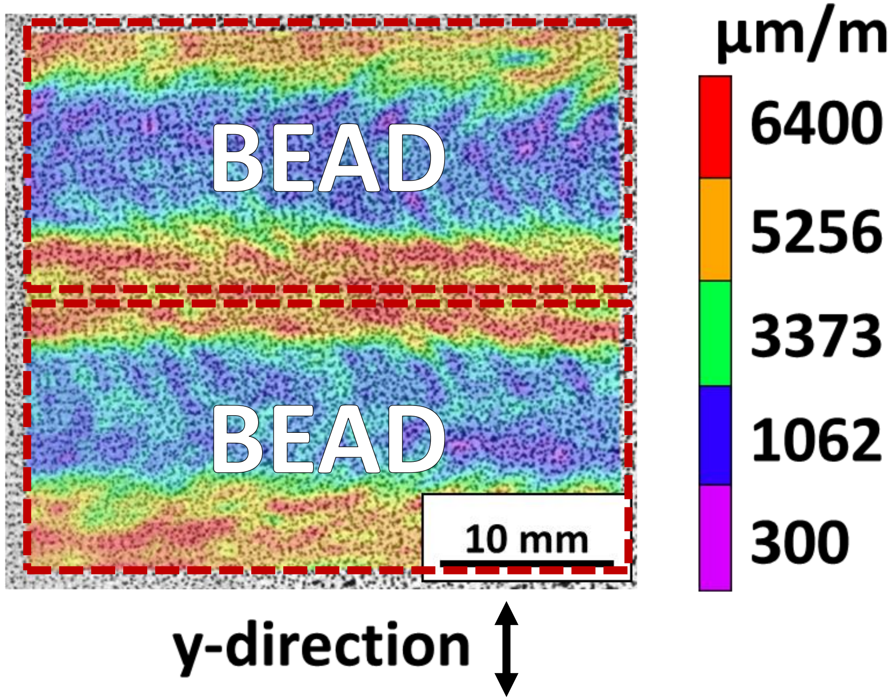
Due to nozzle shear

XY bead view shown here

Strain Map, XY Plane





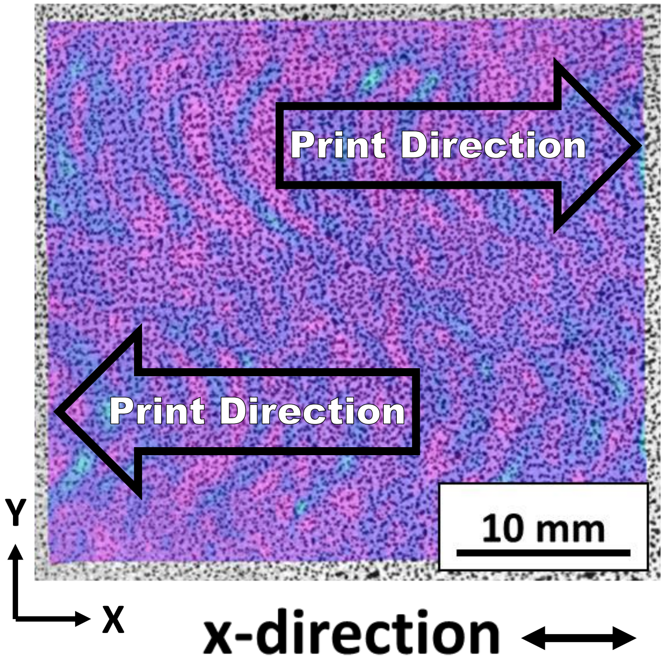


Scallops from print direction

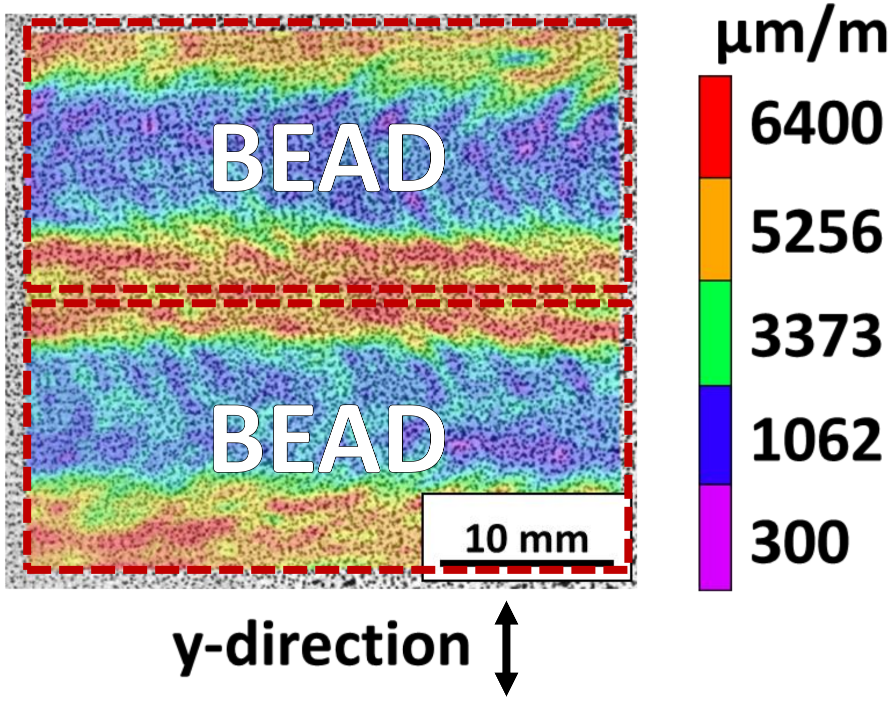
Effects of fiber alignment influencing strain

- Created using Vic-2D
- Homogenous spread of relatively low strain in the x-dir
- Notice red & blue bands of strain in the y-dir
    - Red is high strain at bead edges
    - Blue is lower strain at the more randomly oriented bead center

Strain Map, XY Plane



Scallops from print direction



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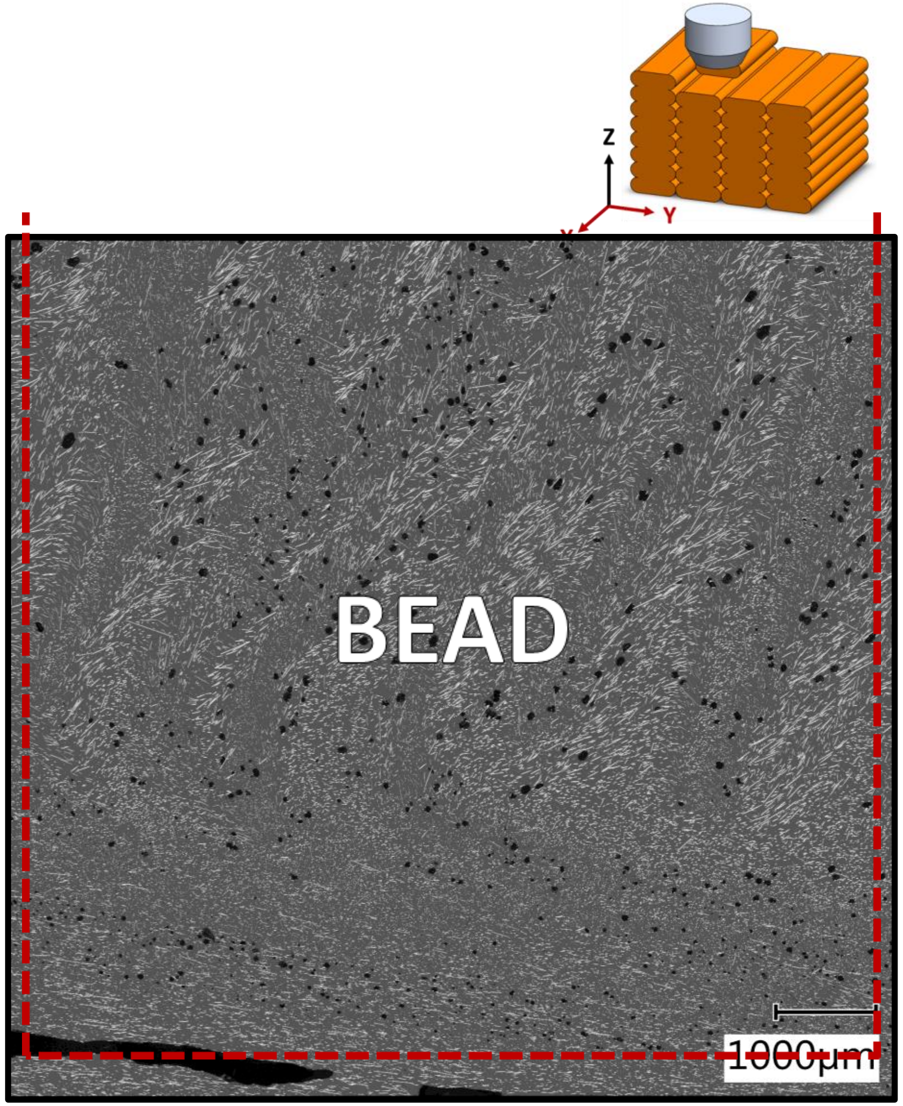
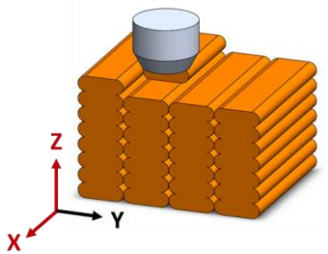
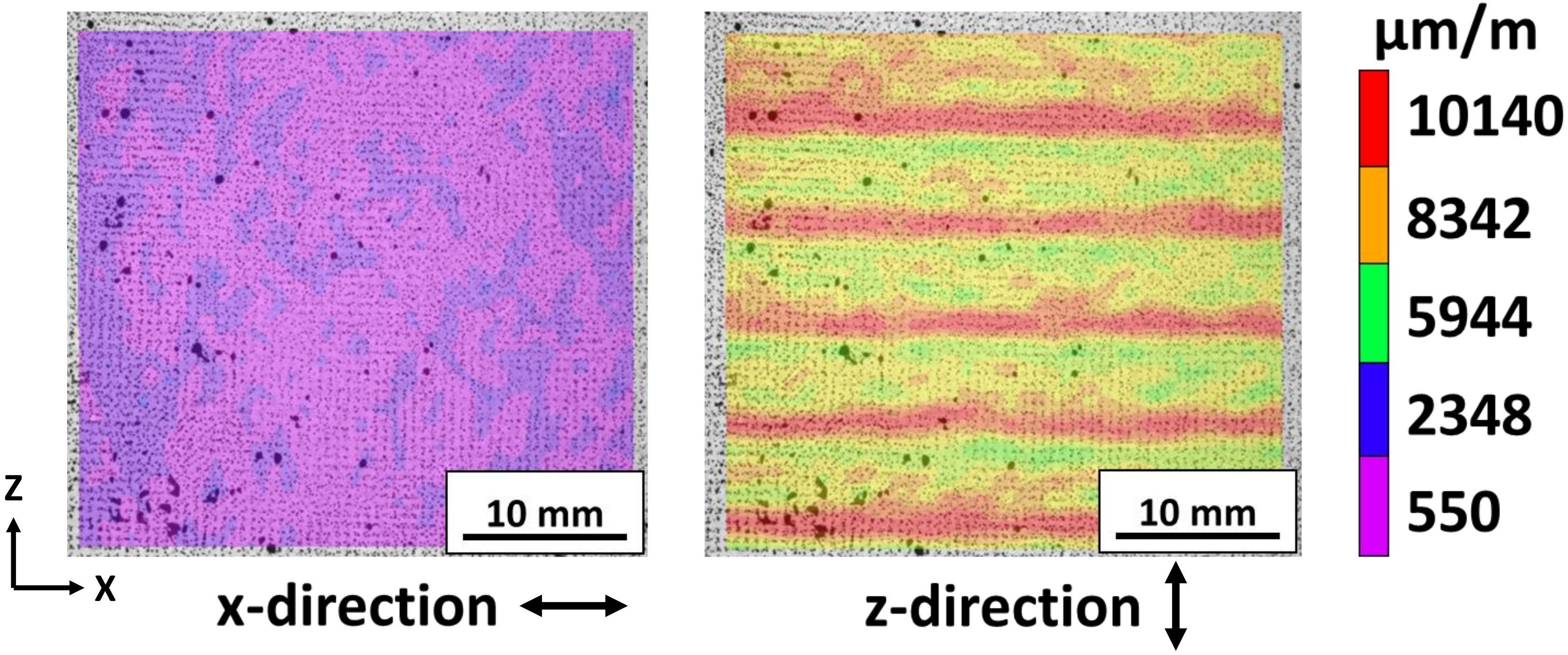


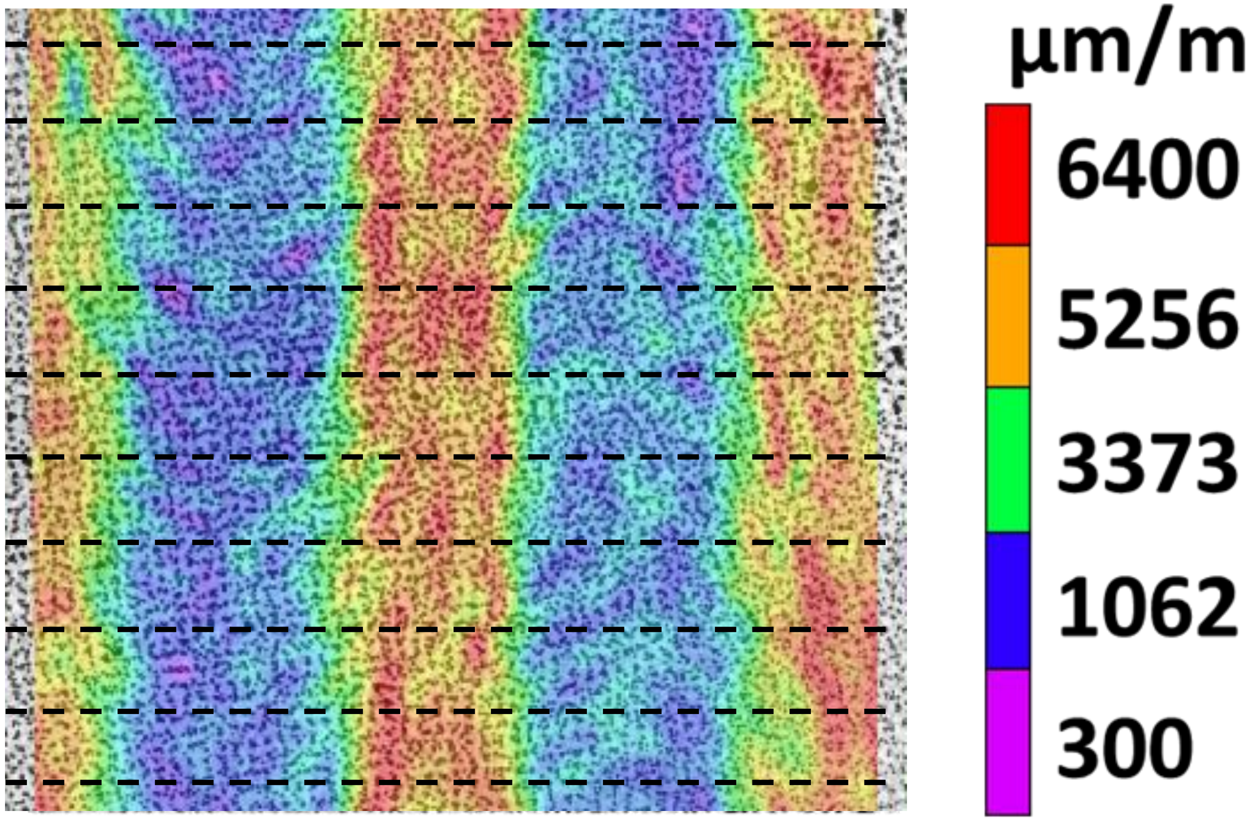
Strain Map, XZ Plane





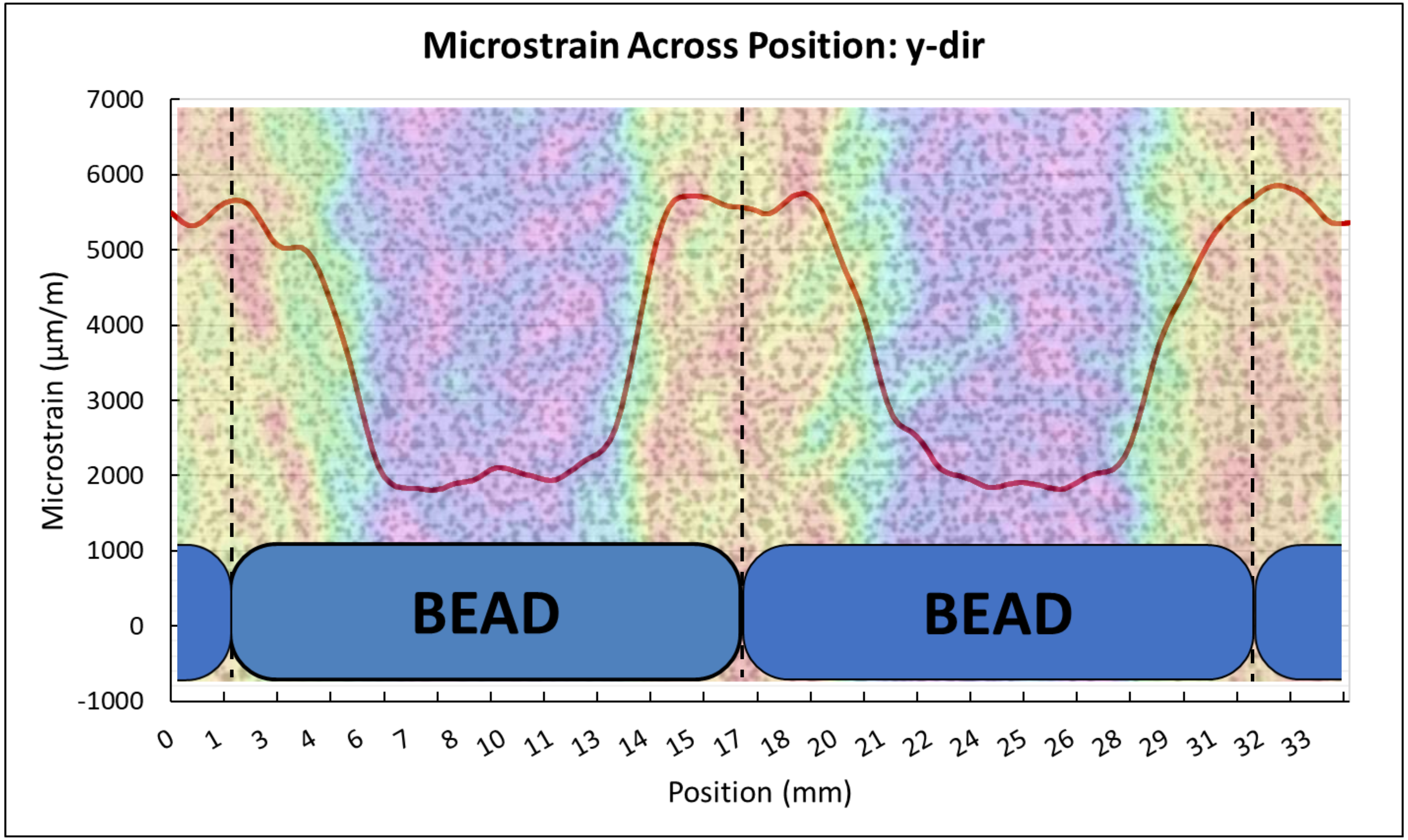
- Created using Vic-2D
- Homogenous spread of low strain in x-dir
- Bands again in the y-dir
  - High strain from aligned fibers at layer interfaces (red)
  - Recall fibers provide **much less resistance** in transverse direction
  - Lower strain from random orientation (orange-yellow)

Strain Plotted



- The following maps the average strain (~2 beads shown here)
- Peaks correspond to highly fiber aligned bead edges
- Valleys are randomly oriented center
- Clearly not symmetric, but repetitive

Strain Plotted



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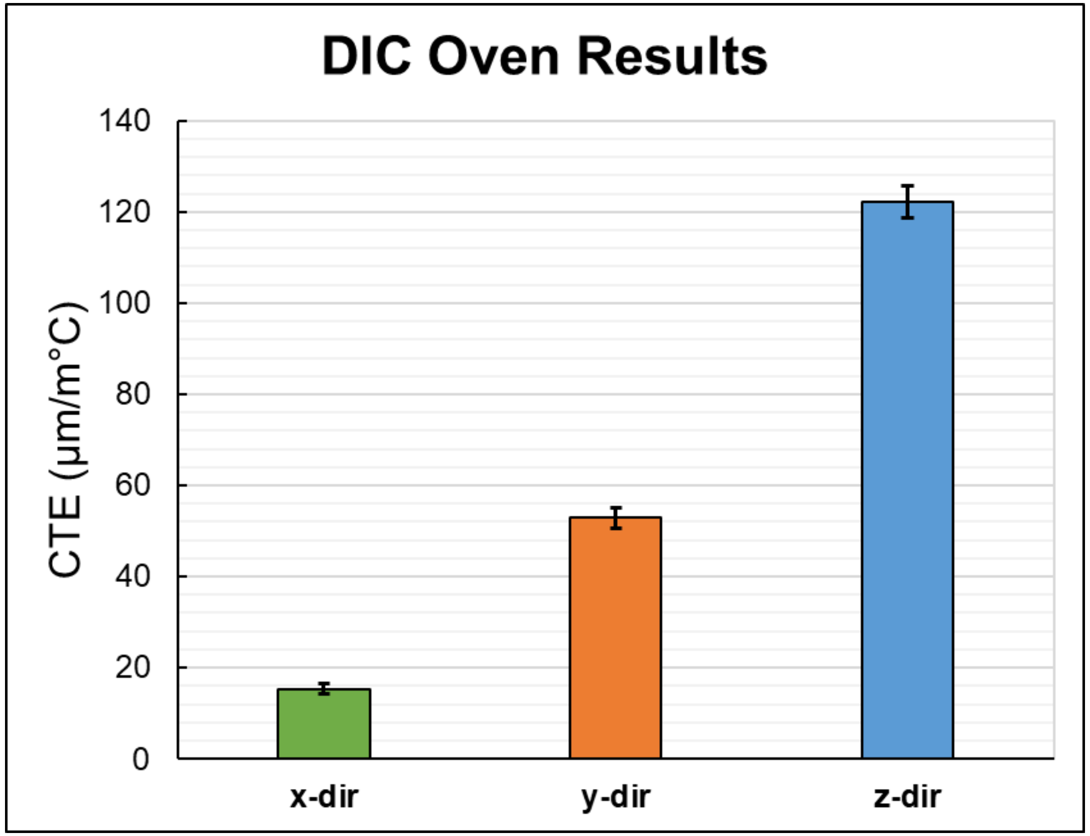
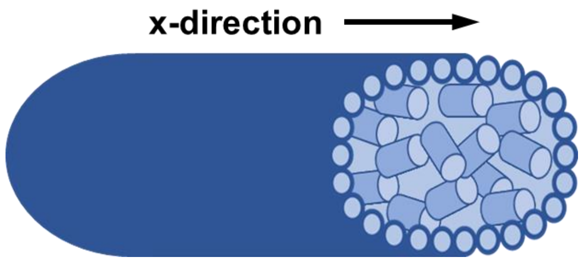
CTE Values – DIC Oven

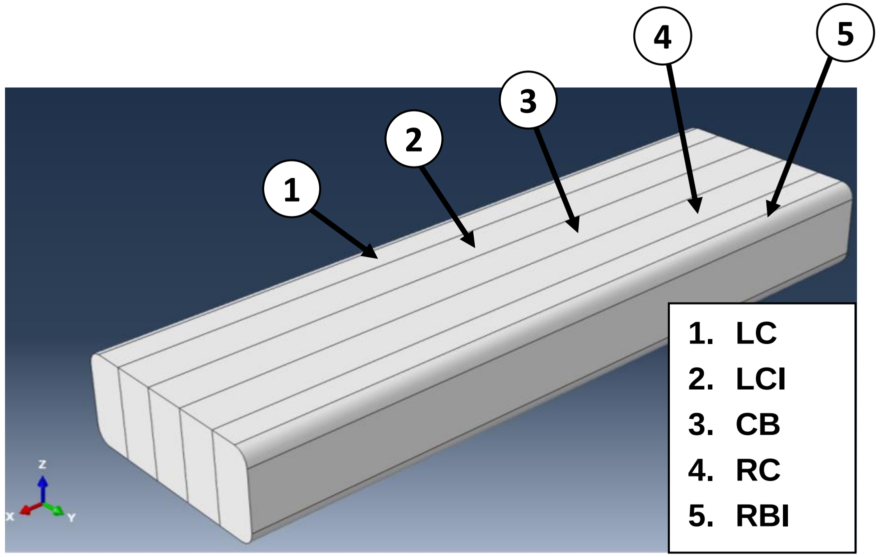


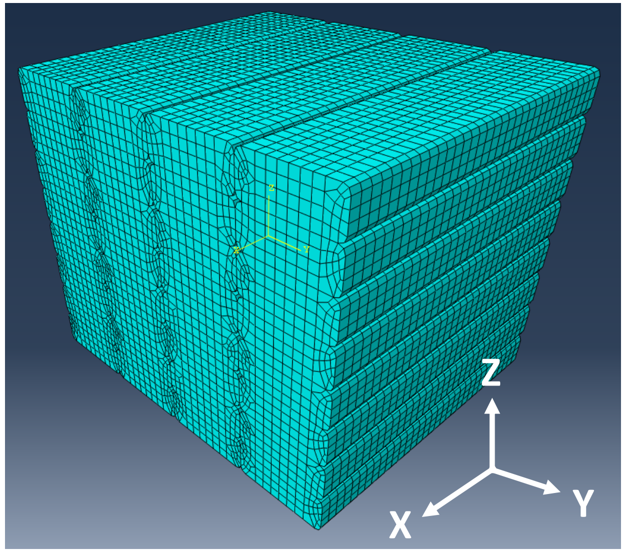
- CTE values measured using the DIC Oven
- X-dir CTE is lowest from fiber aligned in this direction
- Y-dir CTE is higher due to fiber aligned at bead edges & random orientation in center
- Z-dir CTE is highest from fiber aligned along layer edges that provide little resistance to transvers direction expansion



Abaqus Simulation

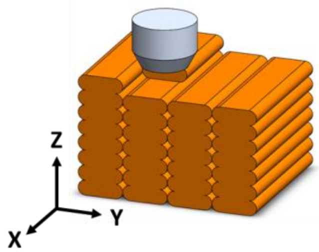
- Modeled LFAM bead to allow multiple CTE inputs from TMA values
- Complex microstructure represented in the mesostructure of the LFAM bead
- LFAM structure (4x8 beads) created from beads to deform as a single part



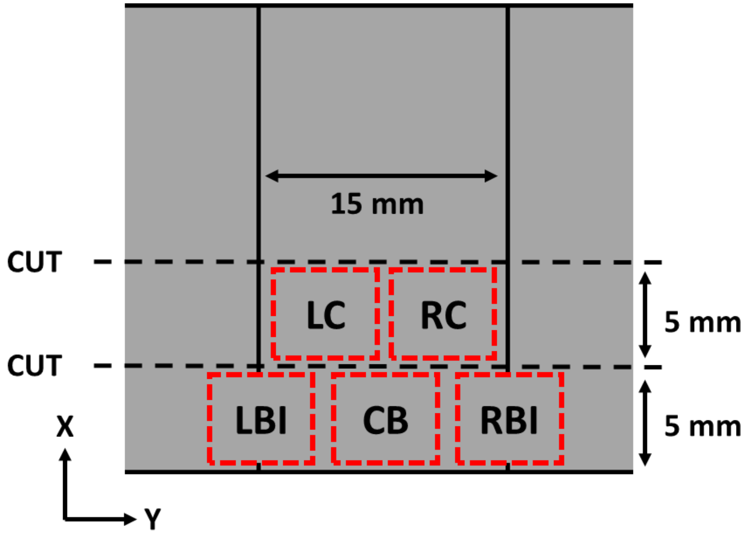


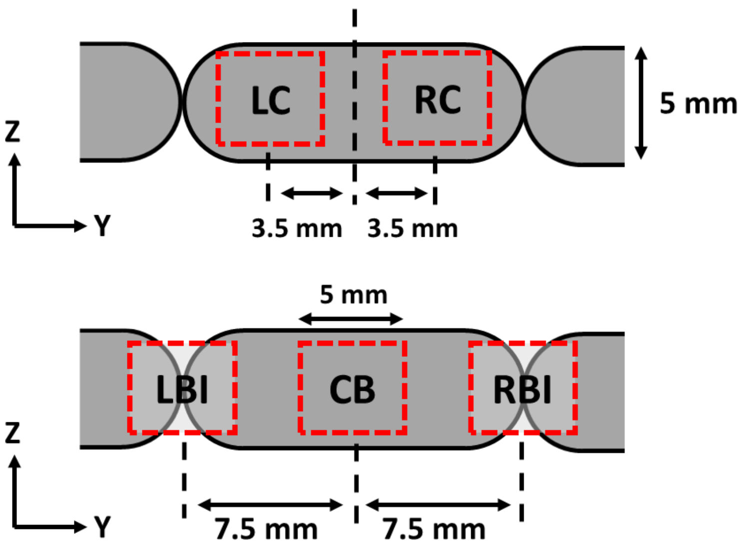
Meshed LFAM sample made from the anisotropic mesostructure of the beads

TMA Inputs



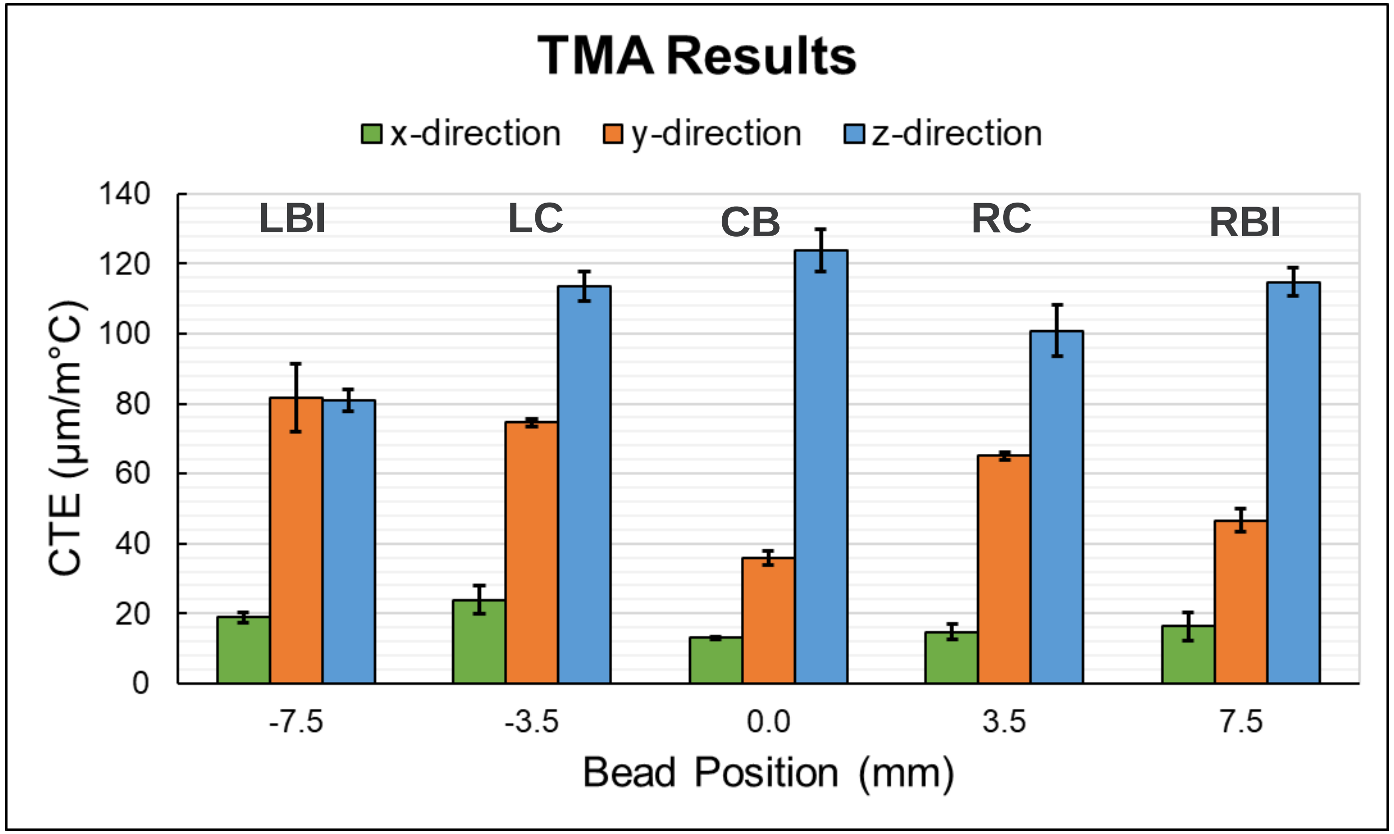
- Use multiple TMA measurements to better capture anisotropic microstructure
- The DIC cube was cut using a diamond saw to test 5 total TMA samples
- Model used TMA values as inputs for different “materials” representative of TMA sample location



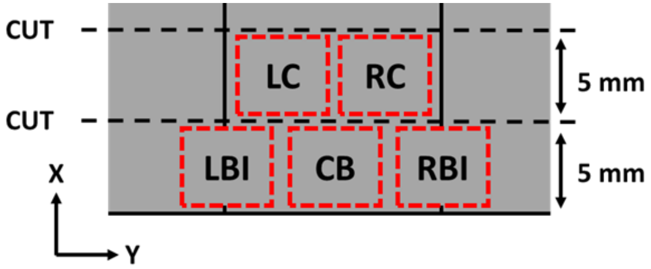


Here: LBI = left bead interface, LC = left of bead center, CB = center of bead, RC = right of bead center, & RBI = right bead interface

CTE Values - TMA



- Over CTE trend of x < y < z
- Differing CTE based on location → fiber orientation
- Suspect LCI ≠ RBI was function of shearing from print path
- Values used as CTE inputs for Abaqus model



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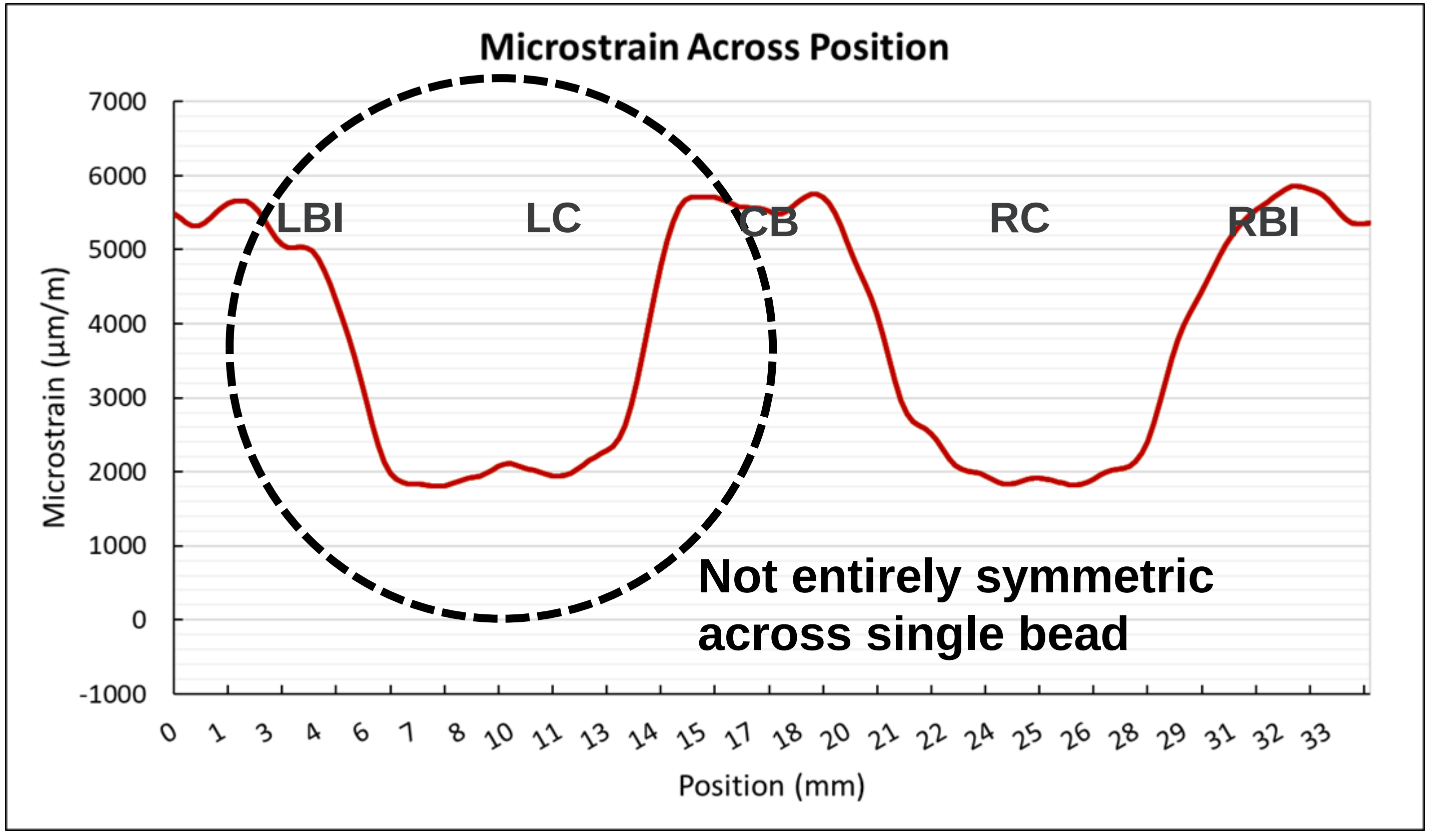

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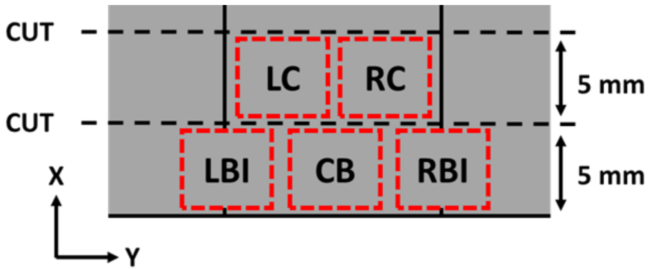
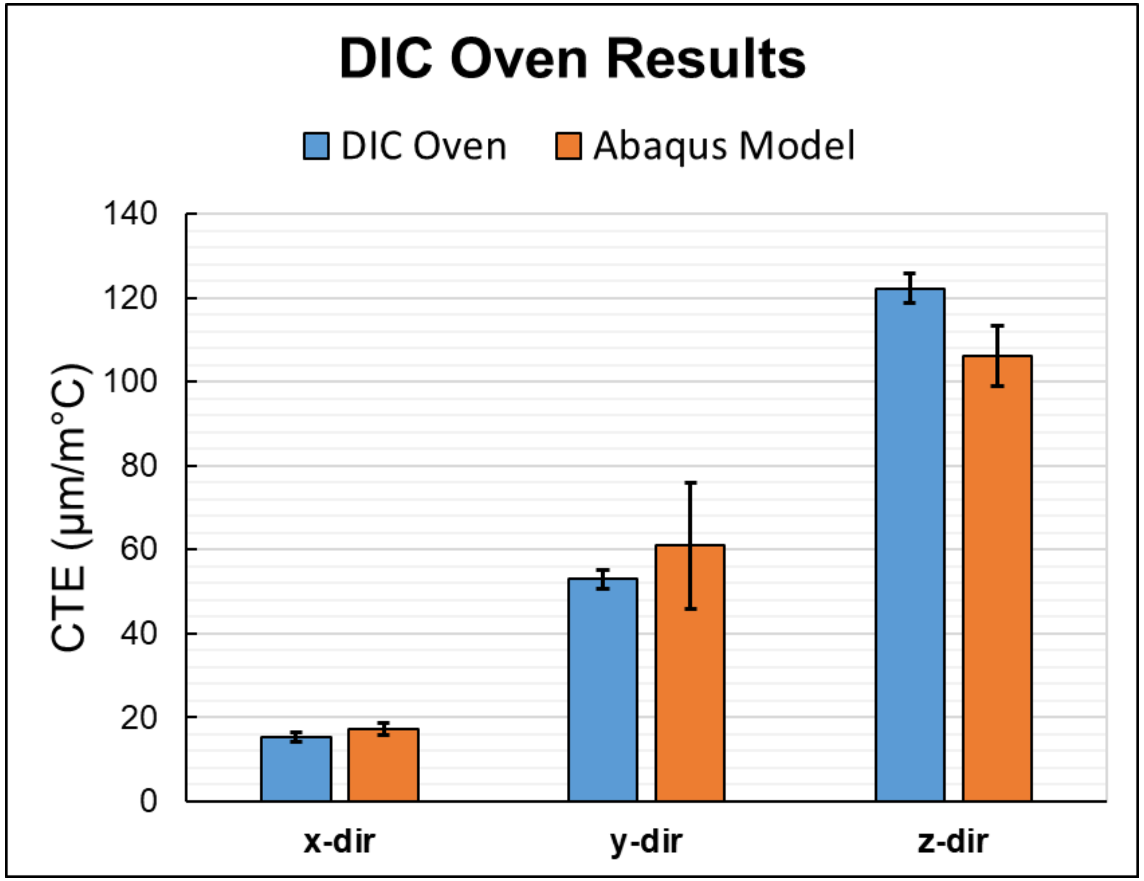
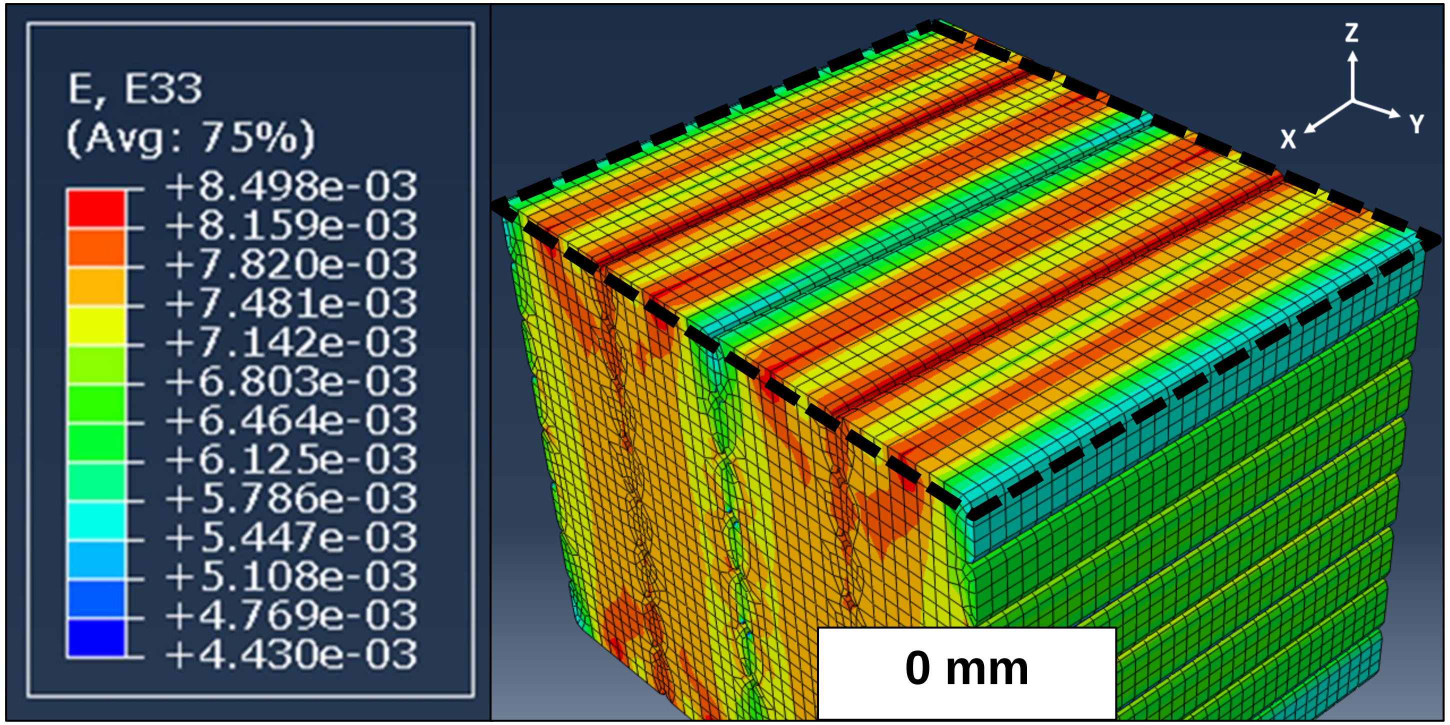


Abaqus Simulation



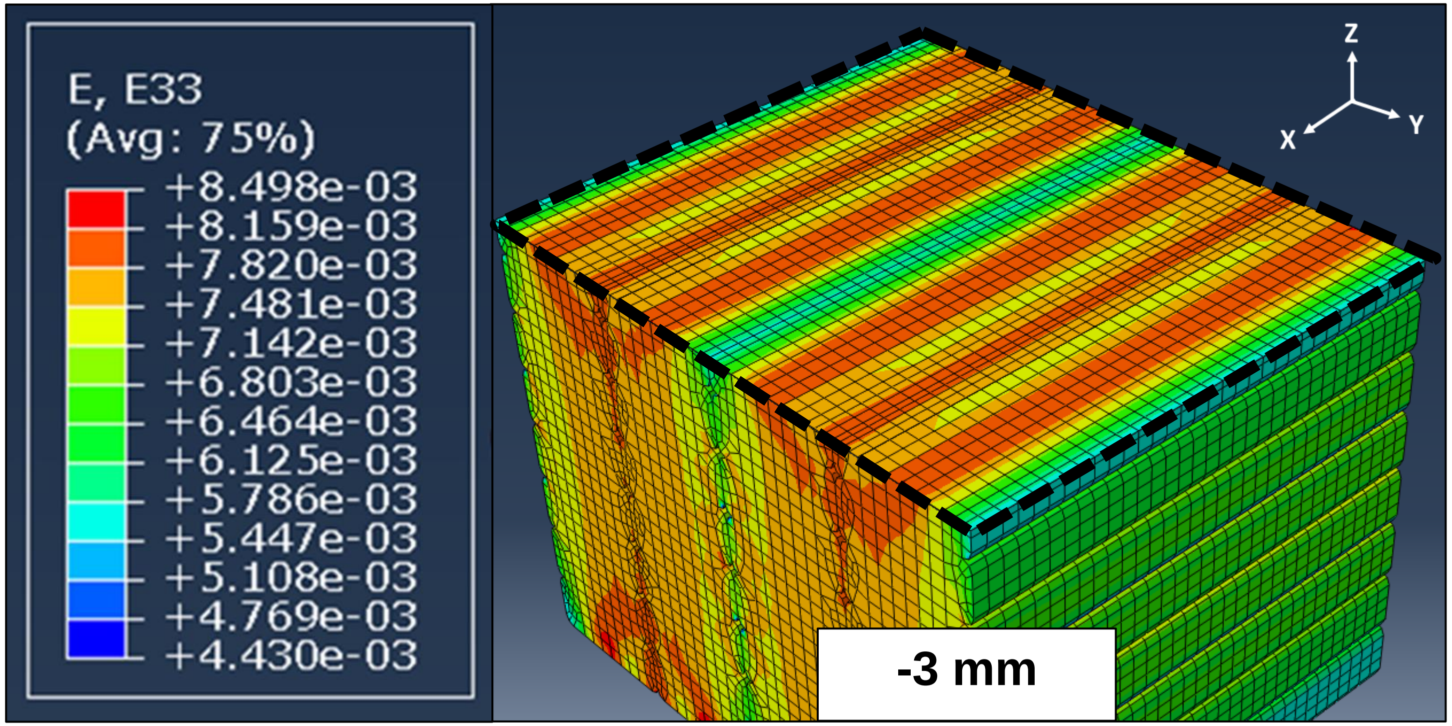
- Modeled vs. measured CTE shown
- Modeled CTE is similar to measured
- The z-dir CTE modeled in Abaqus was lower than measured by DIC Oven
  - TMA inputs struggle to capture deformation between layers
  - TMA is a local measurement where DIC Oven is global

Abaqus Simulation



- Z-dir strain shown at different z-depths
- Changes as depth changes
- Machining depth is important when imaging samples

Abaqus Simulation



Notice changing plane as depth changes → *different fiber orientation*

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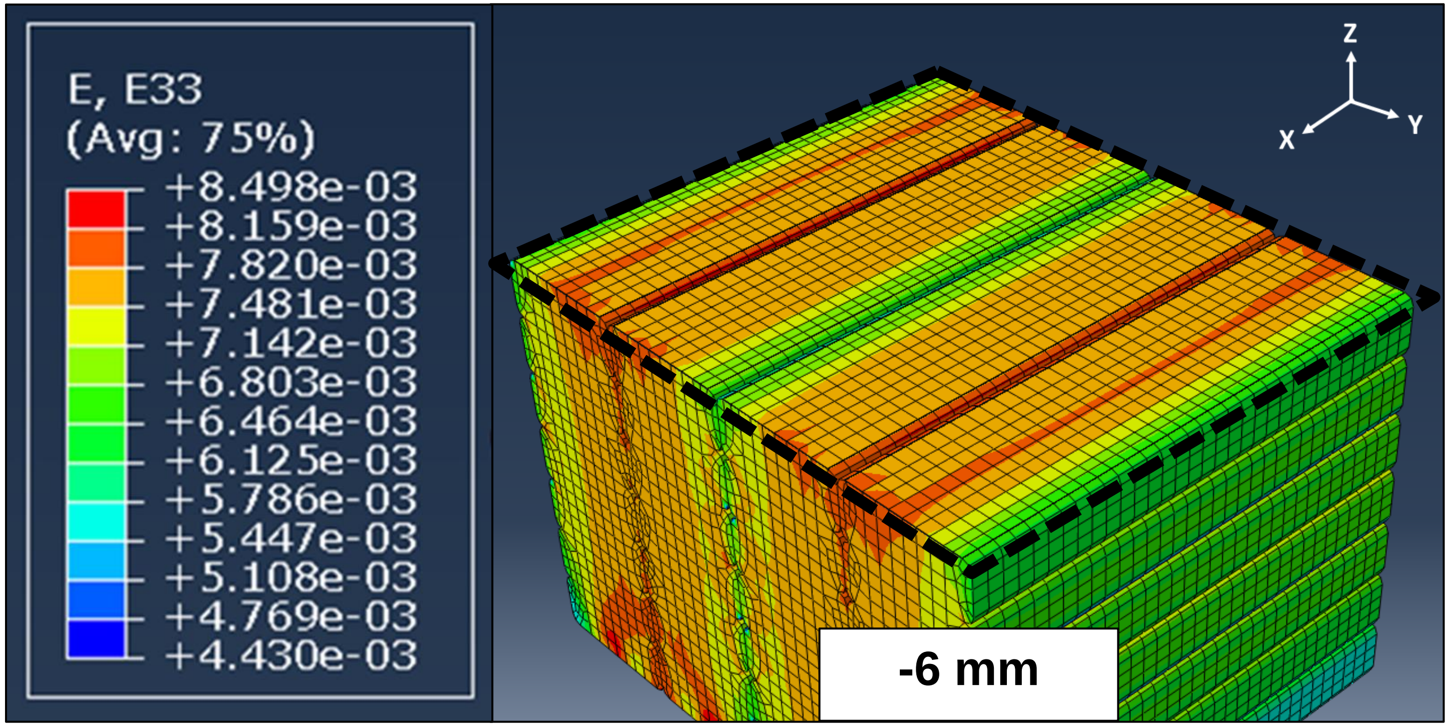

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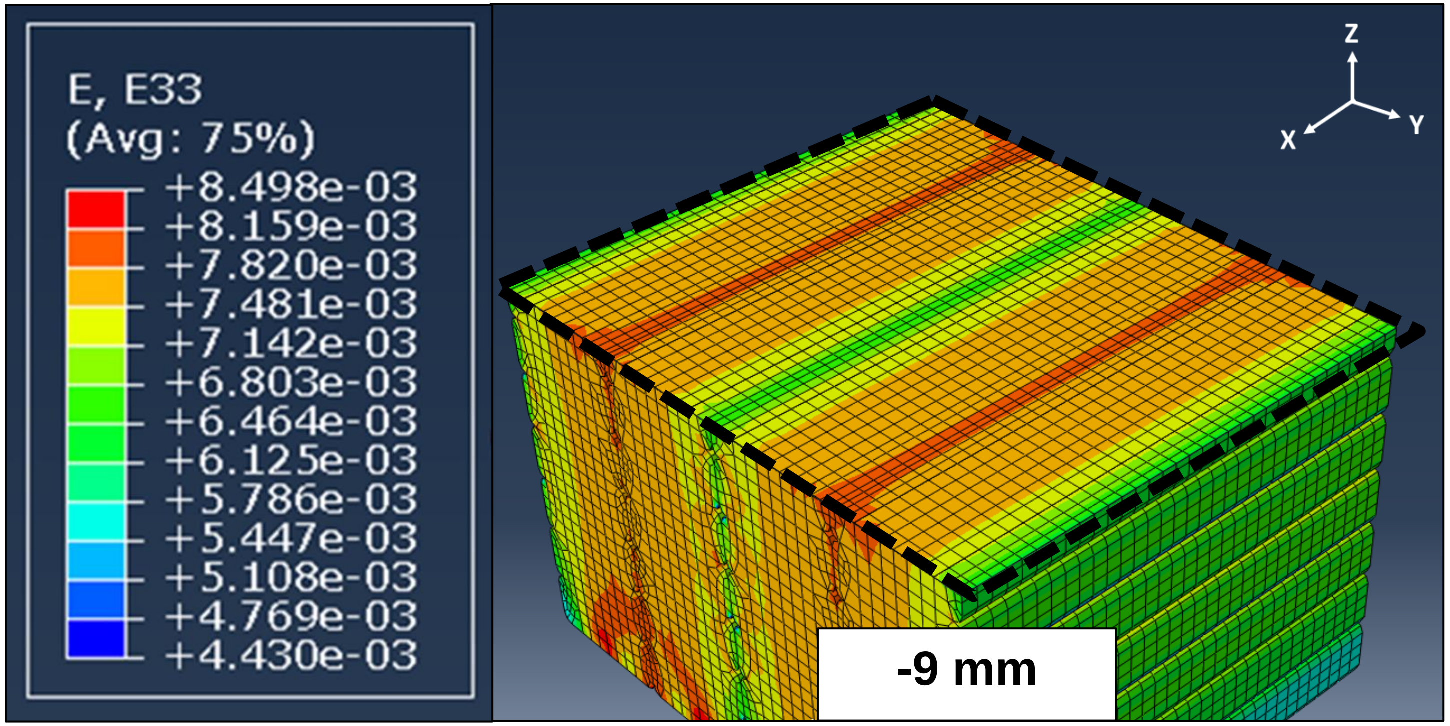

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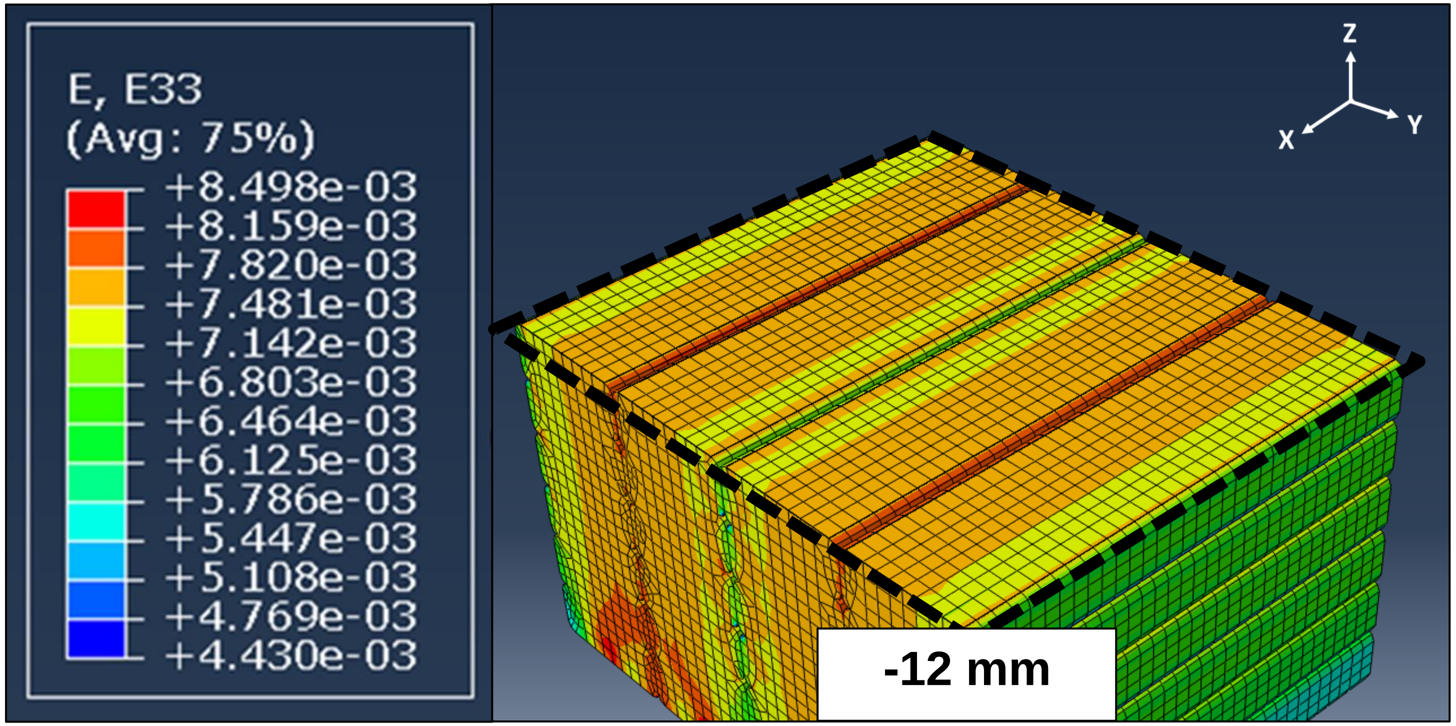
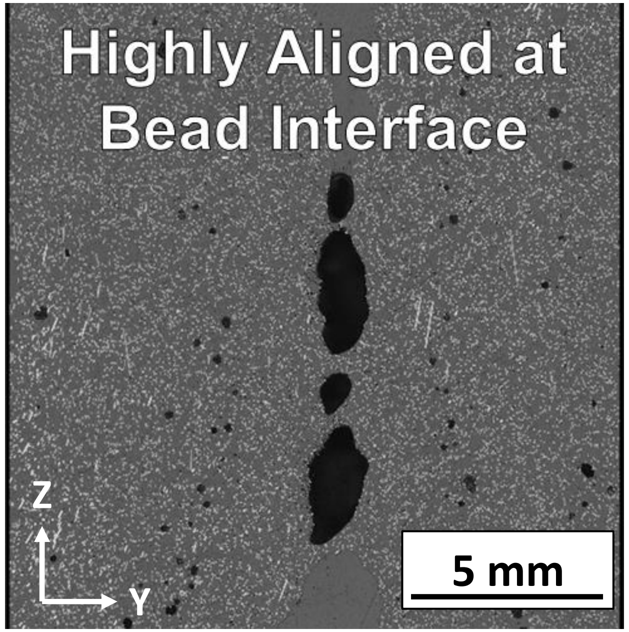


Notice changing plane as depth changes → *different fiber orientation*

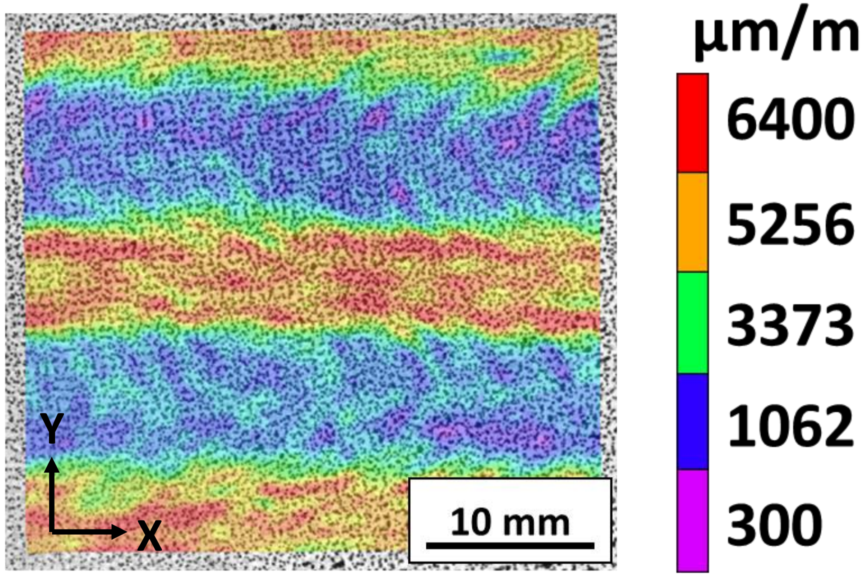
- Z-dir strain shown at different z-depths
- Changes as depth changes
- Machining depth is important when imaging samples

Conclusions

- Fiber orientation directly impacts thermomechanical properties of LFAM structures
- Effects can be visualized using microscopy and measured DIC Oven
  - More aligned fiber at bead edges results in region with higher CTE
  - More randomly oriented center results in lower CTE regions
- Modeling can predict CTE of LFAM structures when inputs capture complex microstructure
- Machining is important as to not skew results

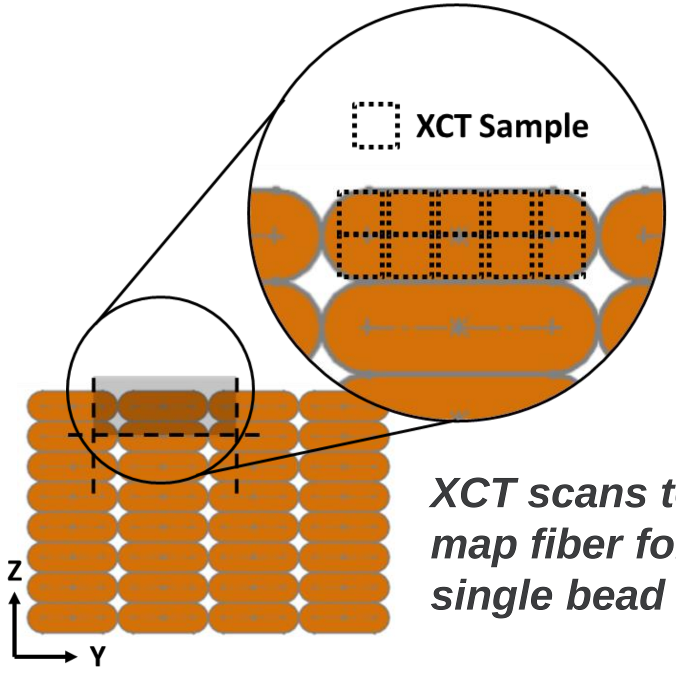


Microscopy image of aligned bead interface (left) & strain map from aligned fiber (below)

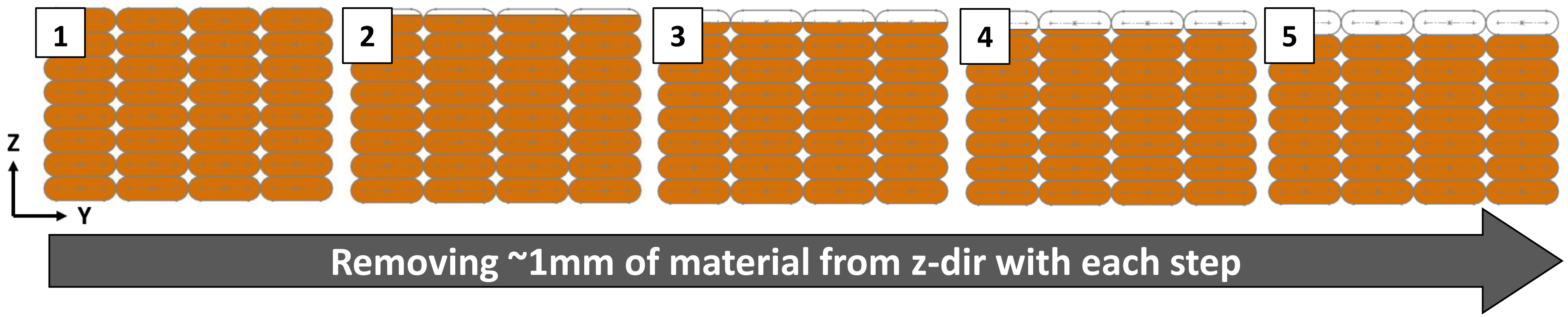


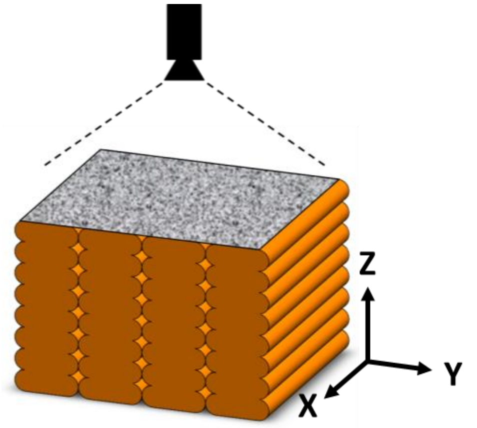
Future Work

- X-ray CT scanning to obtain fiber orientation for a bead profile (right)
- Serial sectioning of CF-ABS sample to verify model results using DIC Oven method (below)



XCT scans to map fiber for a single bead





Acknowledgements

Special thanks to the Southeastern Advanced Machine Tools Network (SEAMTN) at the University of Tennessee, Knoxville for funding this research.

Microscopy performed by Sam Pankratz at the Fiber Composites Manufacturing Facility (FCMF) at the University of Tennessee.

This research was sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

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Thank you for your time!

Any Questions?

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