CHARACTERIZING THE THERMAL-INDUCED DISTORTION OF LARGE-SCALE POLYMER COMPOSITE PRINTED STRUCTURES

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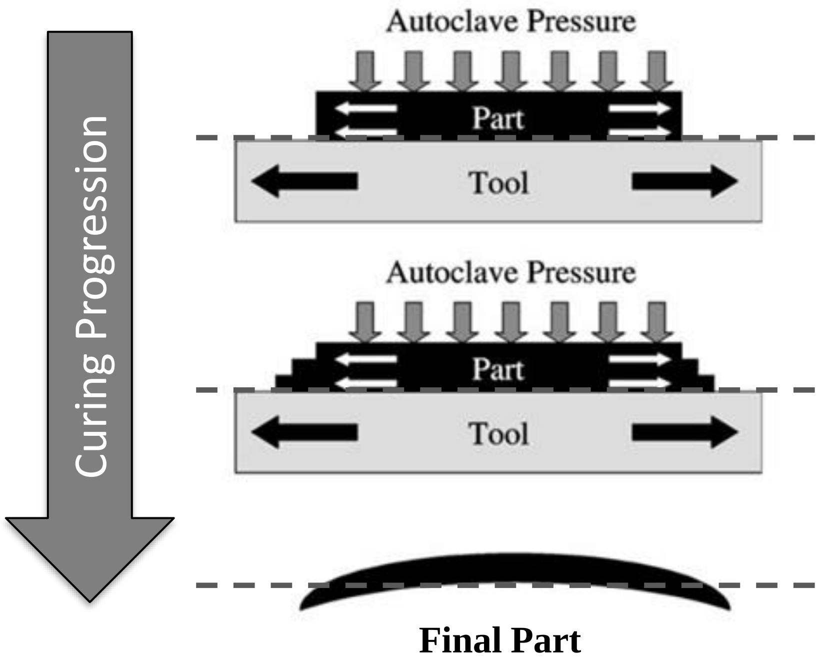
Why measure the thermal distortion of Large-Scale Additive Manufacturing Prints?

The Big Picture of Large-Scale AM

- Large-Scale AM is valuable for tooling applications
- Big Area Additive Manufacturing (BAAM) at Oak Ridges can create large and complex parts
- Fiber Reinforced Polymers (FRP) feedstock increases part stiffness and lowers CTE
- AM tools may still experience warpage at autoclave conditions



Tool warping due to poor tool-part interaction [1]

What leads to this warpage?

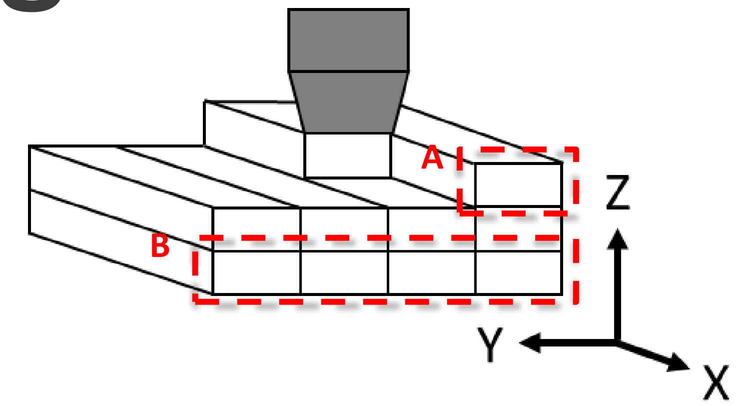
Anisotropic Properties

Anisotropic Material

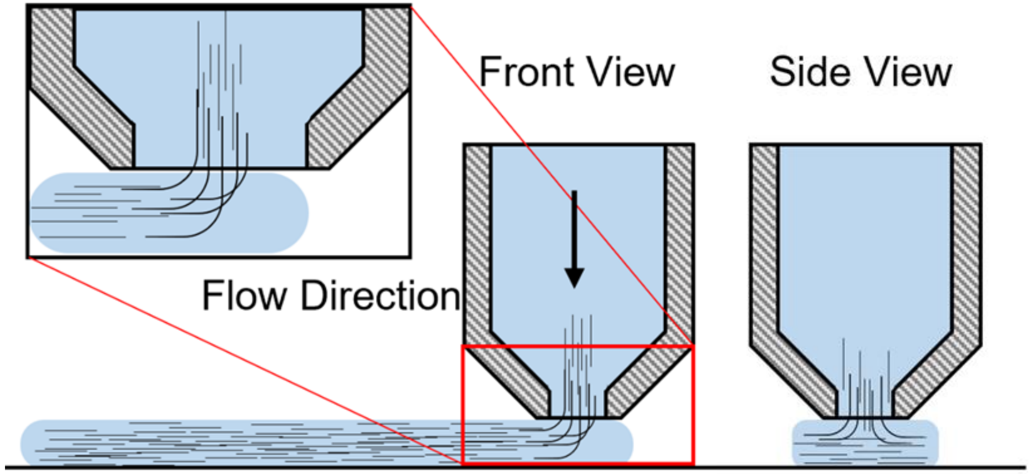
- Fiber Reinforced Polymers (FRP) are anisotropic
- FRP preferred for tooling applications

Mechanically Anisotropic

- Print hierarchy causes different mechanical properties across print
- Fiber alignment from shearing can cause different thermal properties within a layer



Print hierarchy showing a single ***bead*** *(A) vs. a single* ***layer*** *(B)*



Fiber alignment due to nozzle shearing [2]

[2] Colón Quintana et al., *Materials*, Apr. 2022

Traditional CTE Measurement

How have we found CTE values in the past?

Thermomechanical Analysis (TMA)

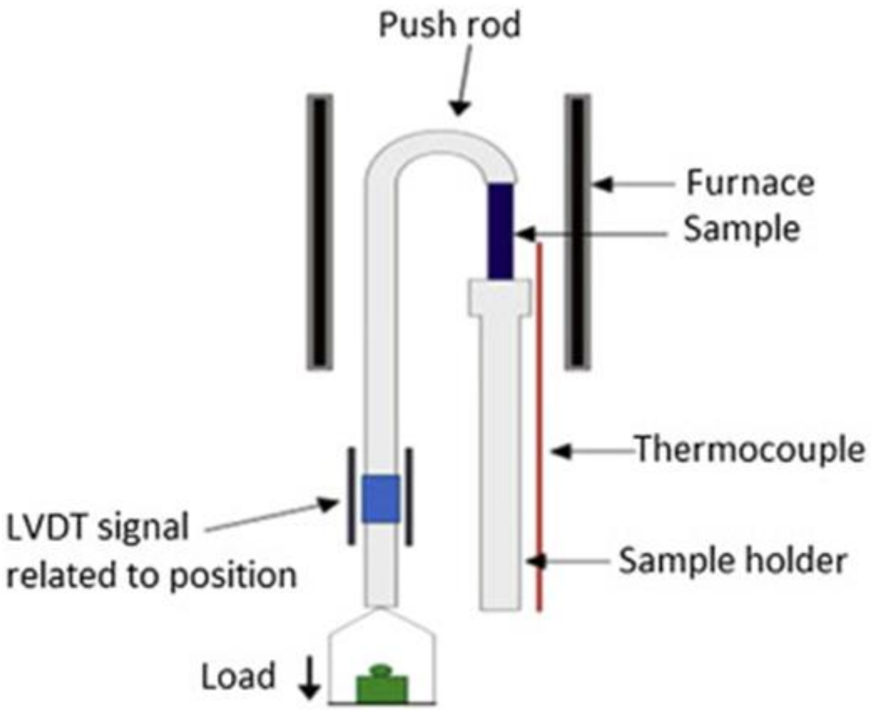
- Traditionally used for CTE measurements
- TMA measures a small specimen *(max size of 10 x 10 x 10 mm) [3]*
- Sample must accurately represent the entire part

TMA measures a small specimen

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

Sample must accurately represent the entire part

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



TMA Schematic with major components [4]

Objectives of this Study

- Improve existing CTE Oven to measure CTE of large-scale AM structures

- Characterize AM print parameters so that orthogonal properties are maximized for tooling

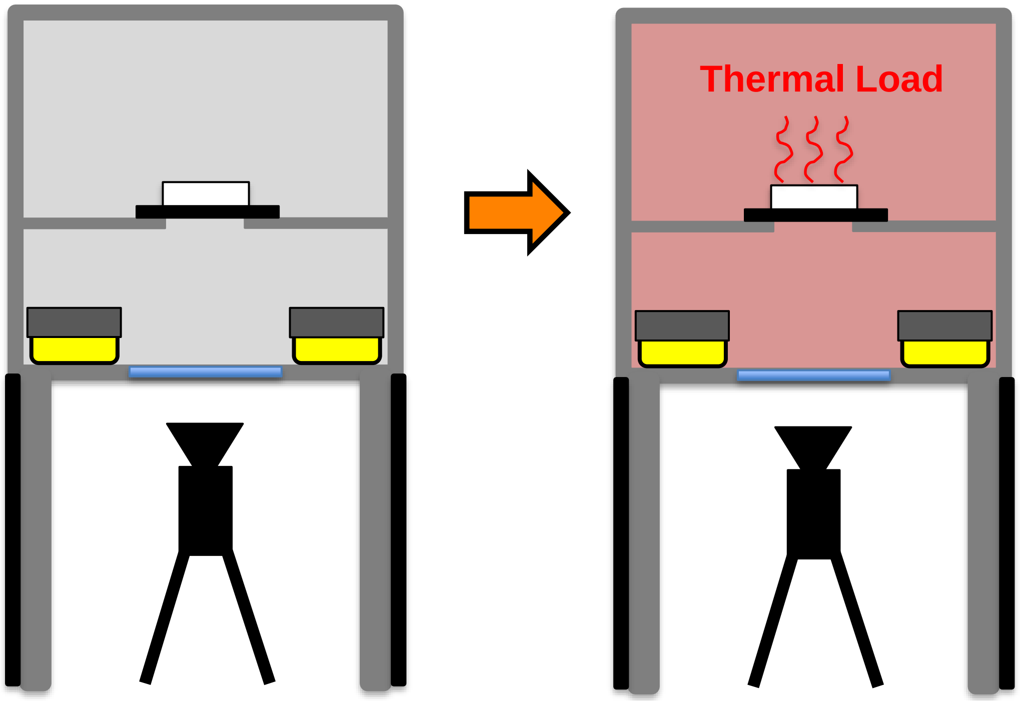
Overview Moving Forward

- CTE Oven
- Test Results
- Conclusions
- Future Work

CTE Oven at the University of Tennessee

CTE Oven Procedure Overview

DIC Speckled Sample



Room Temperature

Steady State Temperature

Procedure Overview

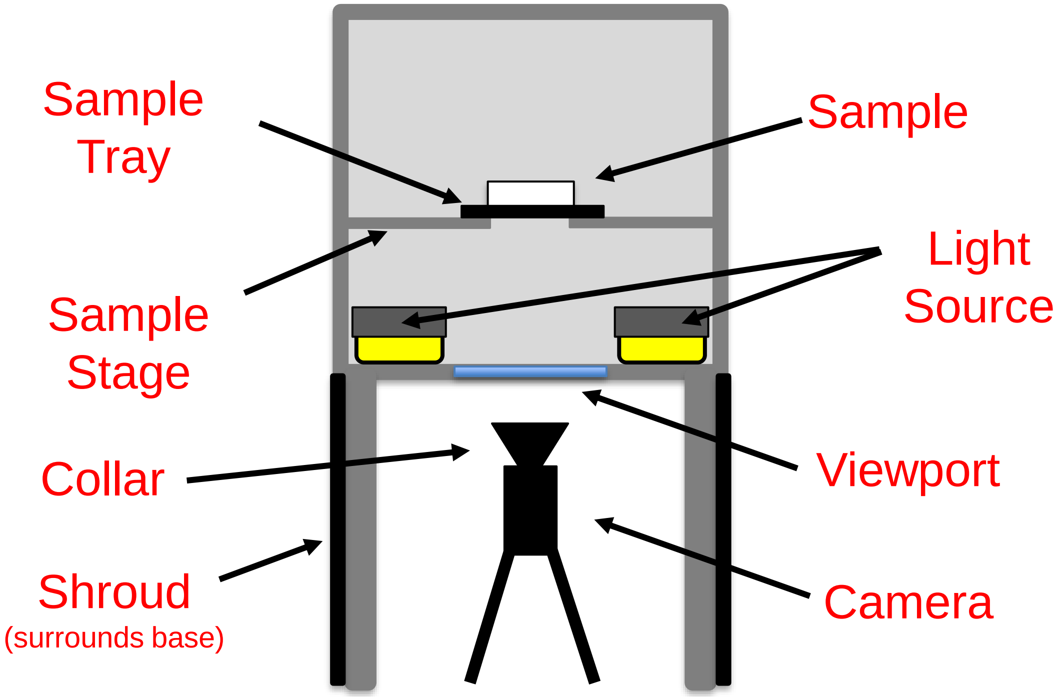
- Set sample
- Room temperature images
- Allow the sample to reach steady state temperature
- Steady state images
- Upload images to Vic-2D software
- Enter data in equation below to find CTE

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

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

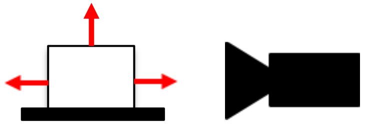
CTE Oven Key Components

External Dimensions: 20.5” x 20.5” x 36”
Internal Dimensions: 15” x 15” x 14.5”



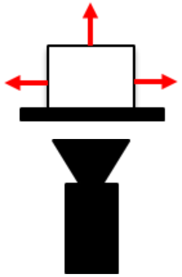
CTE Oven schematic of major components

Typical Camera Position for DIC



The camera will falsely read the expansion towards itself as additional surface movement

Novel Camera Position for DIC

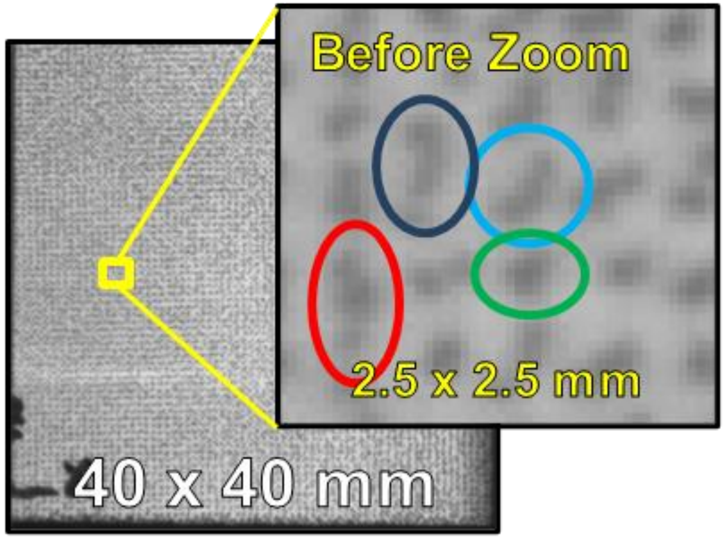


The sample expansion significantly reduce false reading to the DIC software

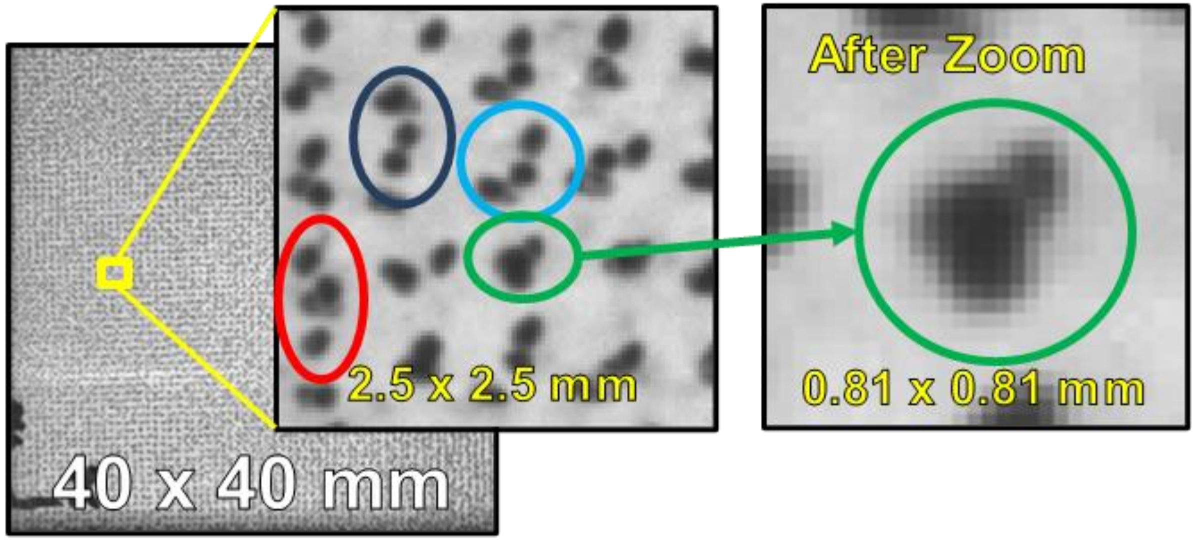
Reasoning behind the Camera Placement for DIC

Focus and Resolution

Before Improvements

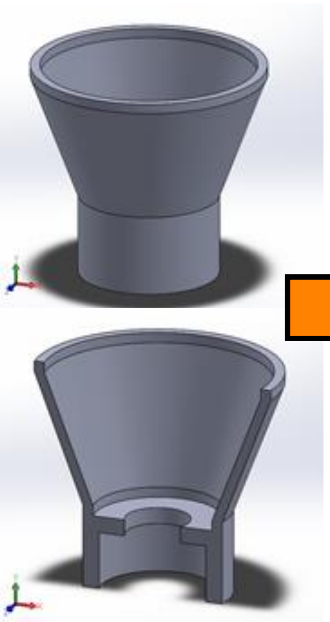


After Improvements



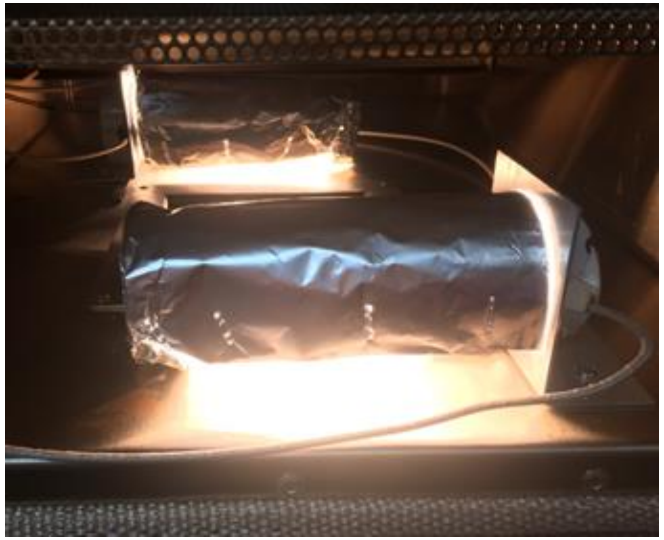
- Camera tripod was positioned closer to the sample
- More defined speckles are easier for DIC tracking
- Pixel resolution increased from **60 to 28 microns/pixel**

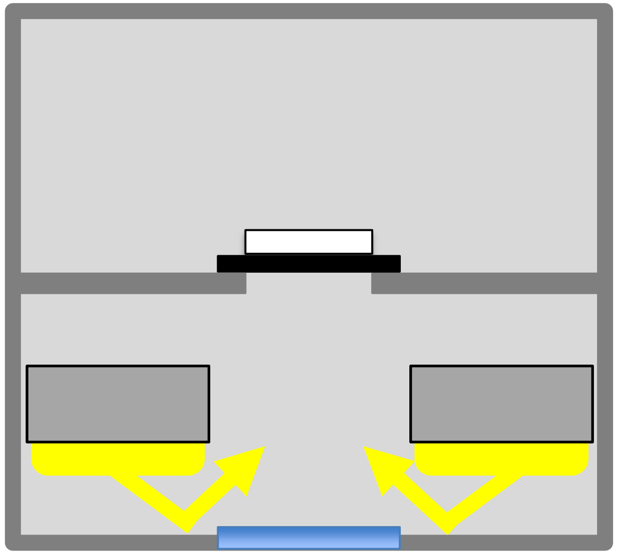
Glare Reduction



- Camera was seeing its own reflection
- Collar was added to improve image consistency
- The Collar minimized both glare and any dust seen by the camera

Improved Lighting

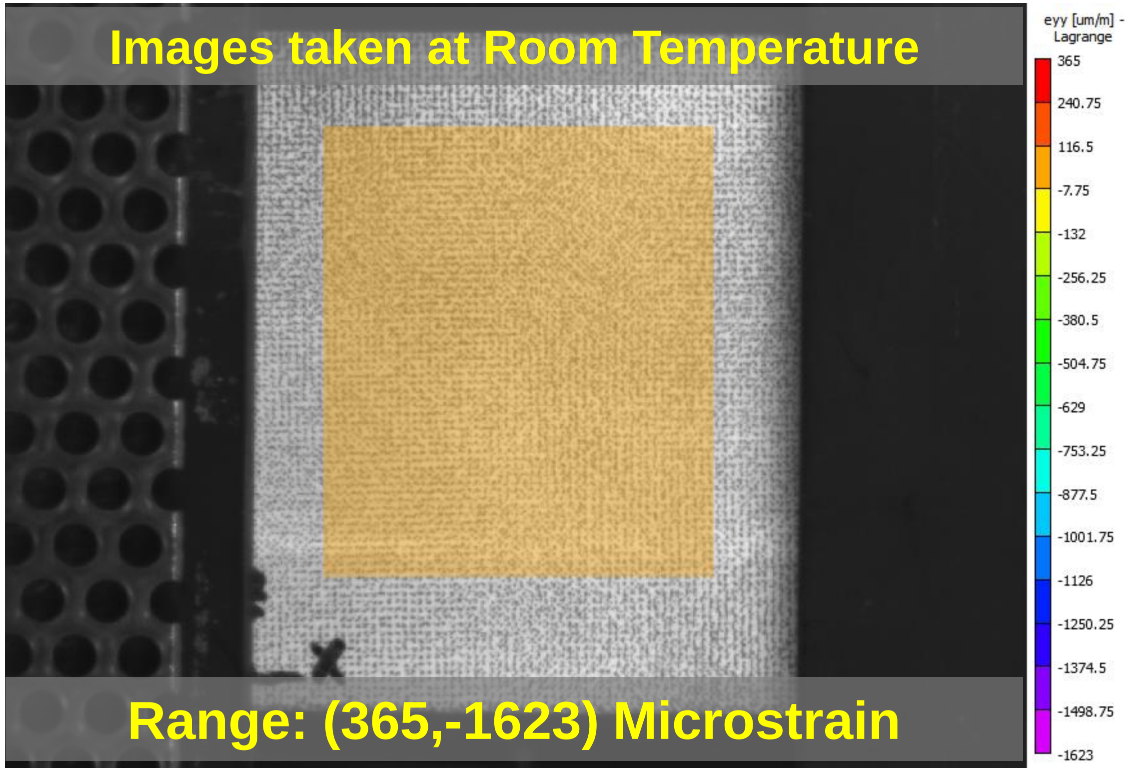




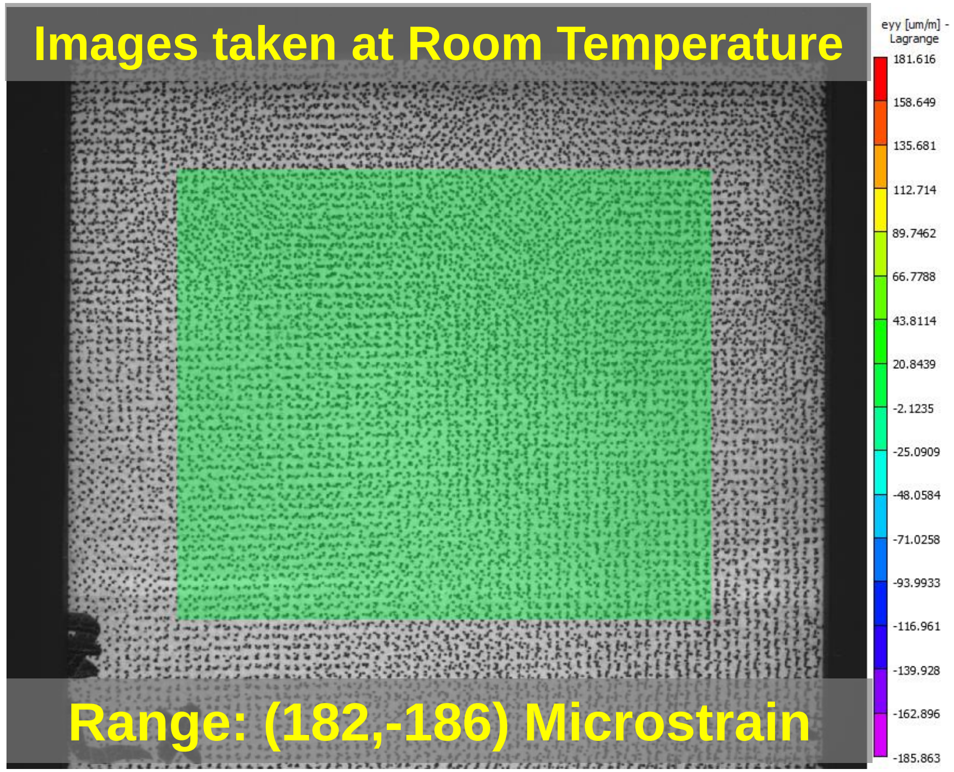
- Lighting was diffused to better disperse and evenly light the sample
- The lighting was angled to light the sample indirectly and reduce glare
- This improved image quality

2D Strain Map

Before Improvements

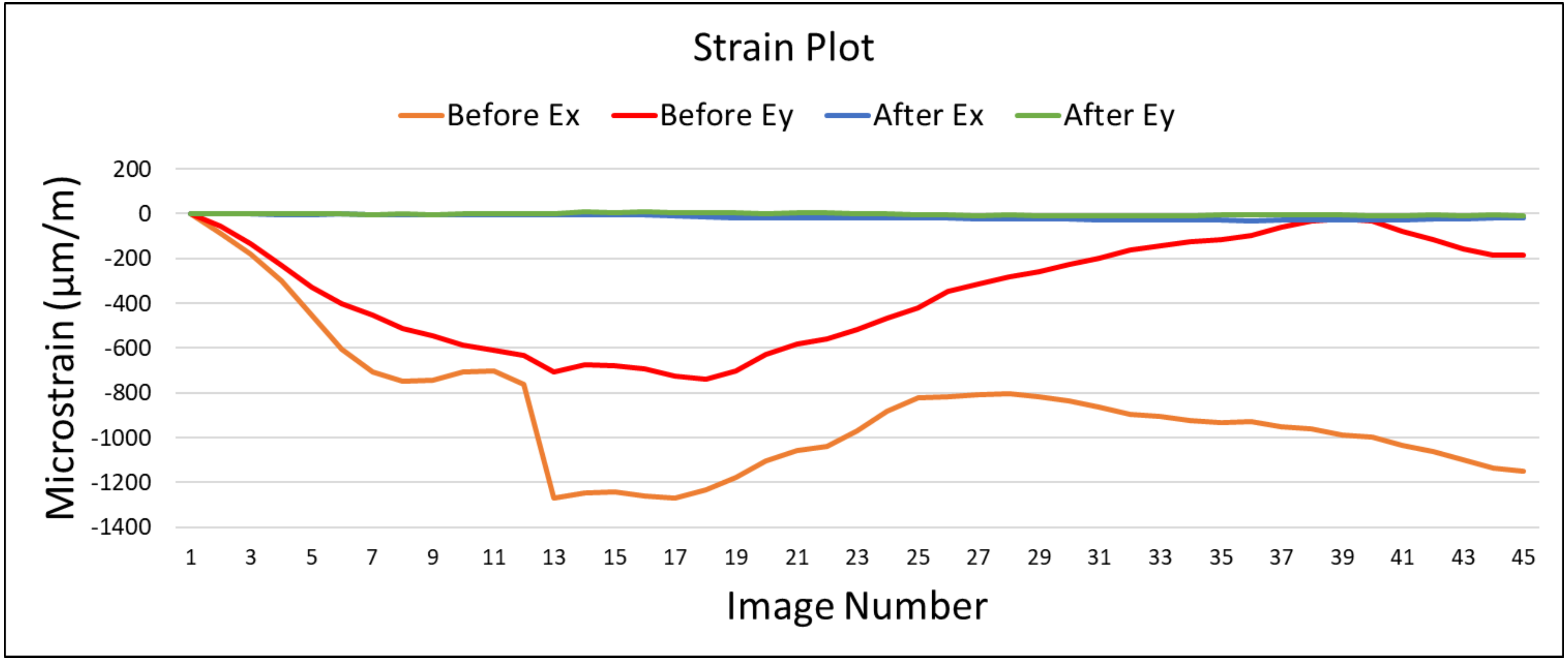


After Improvements



The range of system noise was greatly reduced and the large clusters referred to as “ghosts” were minimized

Strain Plot



The range of system noise was greatly reduced and the data is now centered around zero

Aluminum Calibration

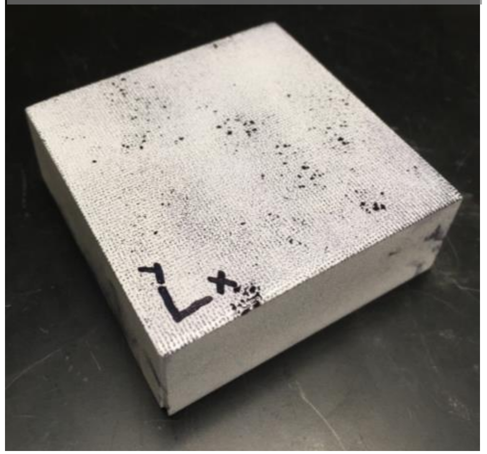
TMA Results (µm/m°C)		
	X-direction	Y-direction
Run 1	24.0	23.8
Run 2	22.6	23.2
Run 3	22.6	23.3
Avg	**23.0**	**23.5**
StnDev	**± 0.823**	**± 0.329**

CTE Oven Results (µm/m°C)		
	X-direction	Y-direction
Run 1	23.5	23.9
Run 2	23.5	24.1
Run 3	23.8	24.4
Avg	**23.6**	**24.1**
StnDev	**± 0.168**	**± 0.259**

- Aluminum was used as homogenous reference material
- Samples were taken from this aluminum for TMA and CTE Oven
- Both systems ran several times to assess accuracy and precision
- Similar values obtained from the CTE Oven and TMA
- Notice standard deviation for the CTE Oven **< 1 part/million**

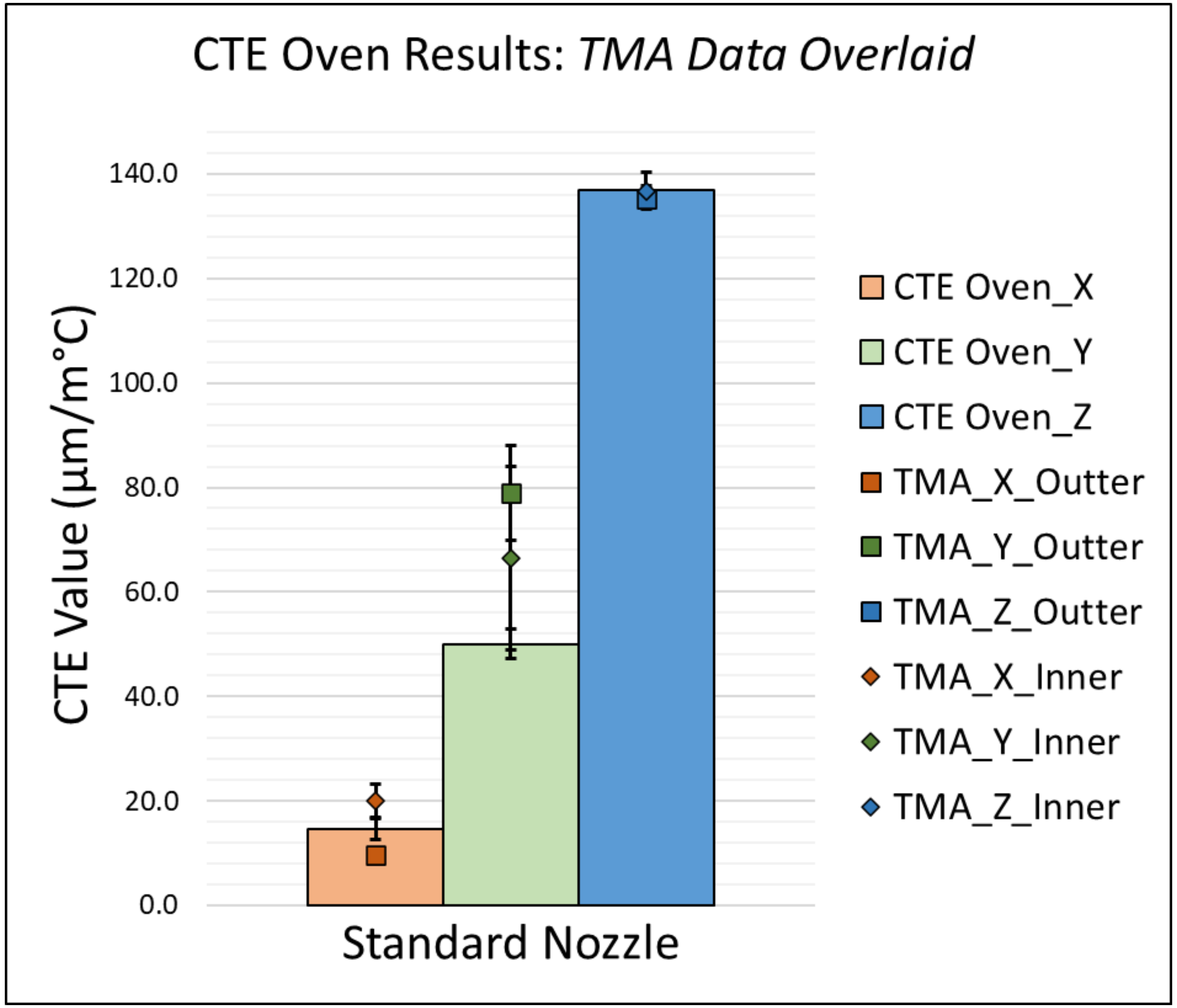
100 x 100 x 100 mm

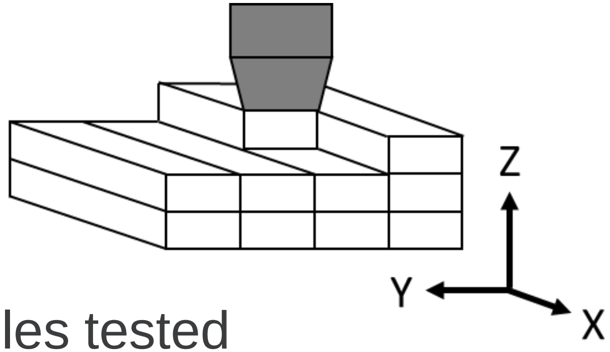
50 x 50 x 20 mm



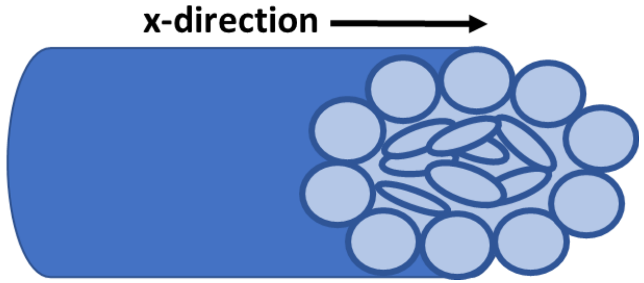
Aluminum Calibration Block

CTE Values



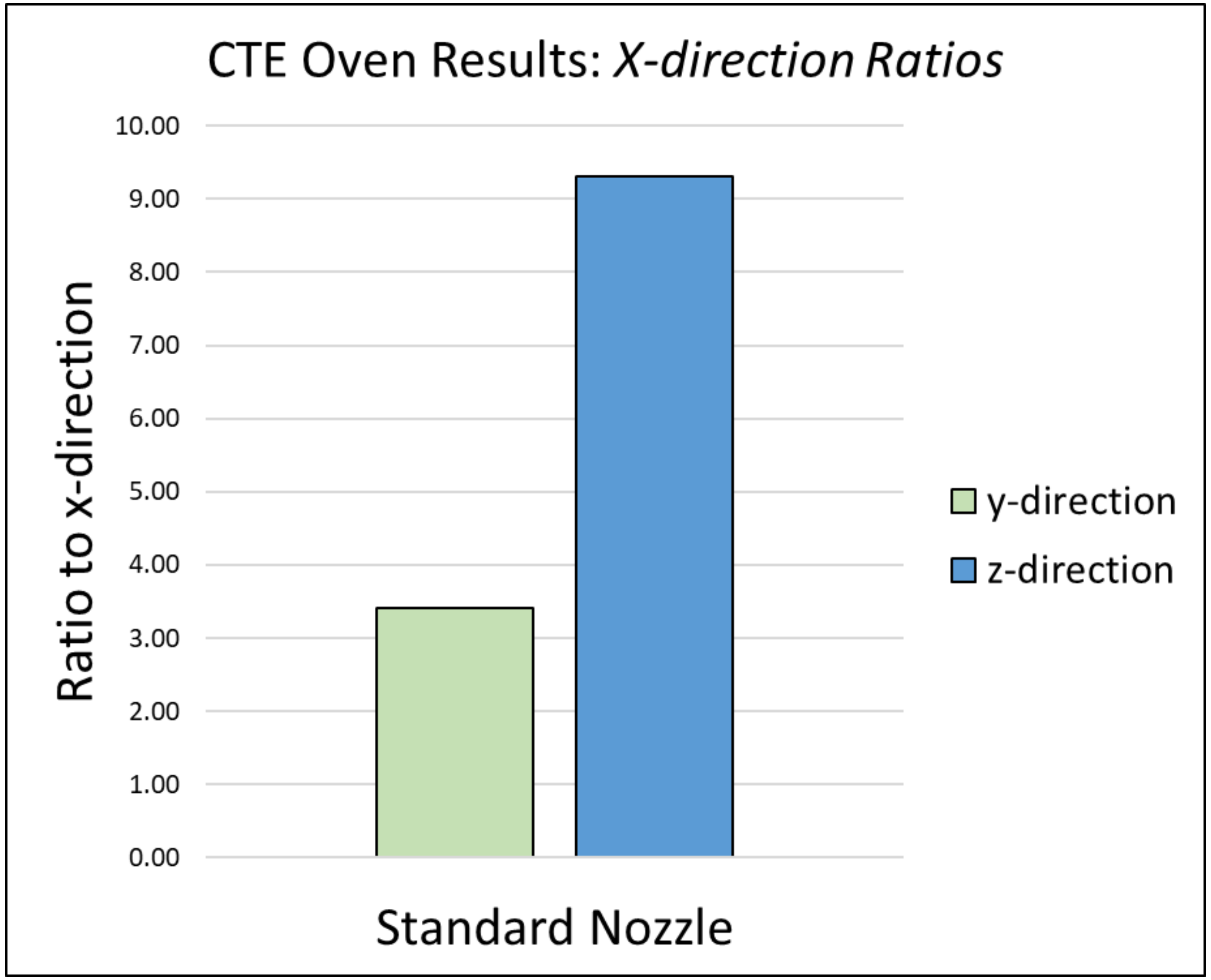


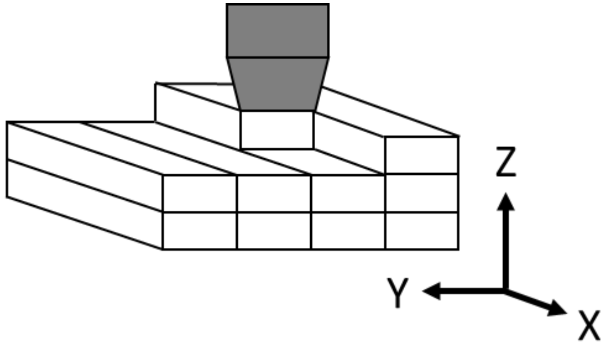
- CF-ABS samples tested
- TMA data overlaid for reference
- X-direction experiences the lowest CTE and the Z-direction sees the highest CTE as expected from fiber alignment
- CTE data agrees with TMA



Fiber alignment from nozzle shear

CTE Ratios



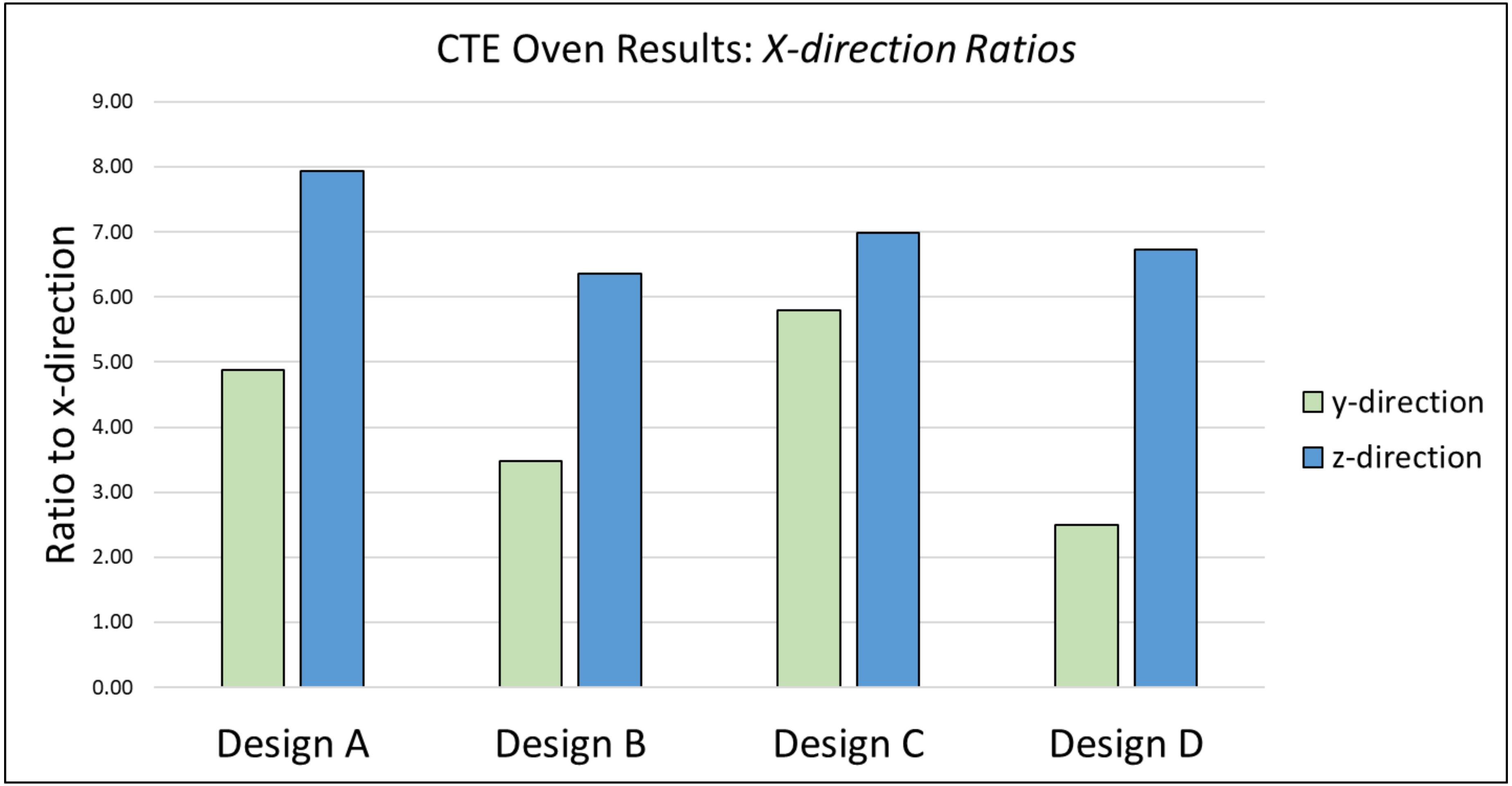


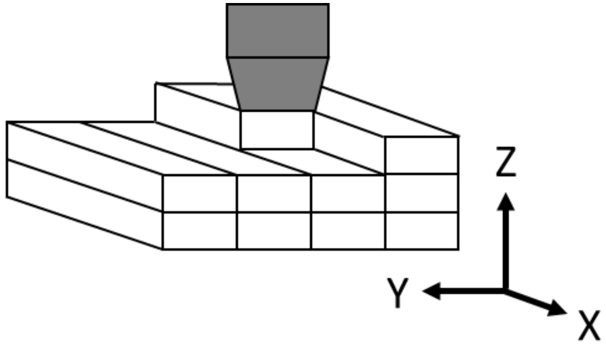
- Orthogonal ratios for the standard nozzle shown
- Orthogonal ratio represents numerically how CTE in both y and z are related to CTE in the x-direction

(value of 10 means 10 times higher than x)

- Ideally value would = 1 for each direction
- Tooling sees best results from orthogonal planes

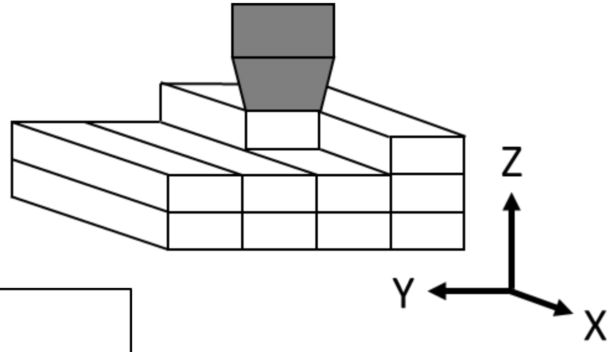
CTE Ratios

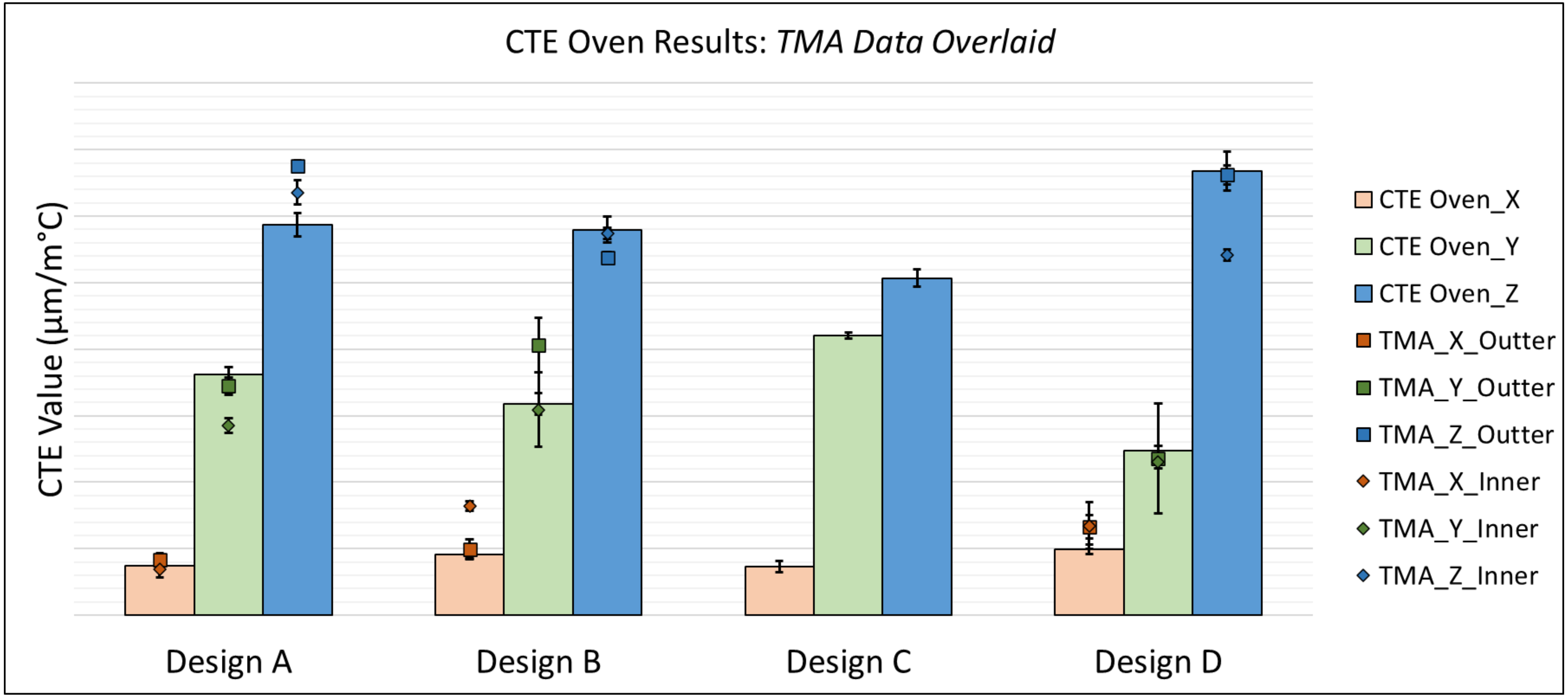




- Orthogonal ratios for each y and z for each x
- Very difficult to lower both y and z
- Controlling orthogonal properties is possible!

CTE Values

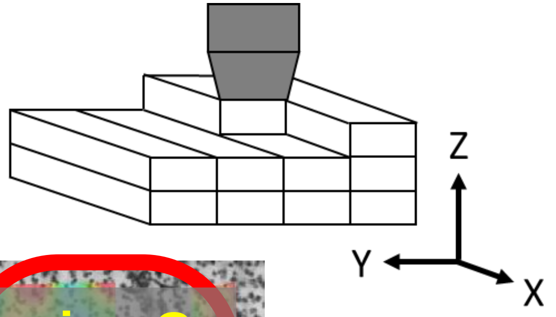


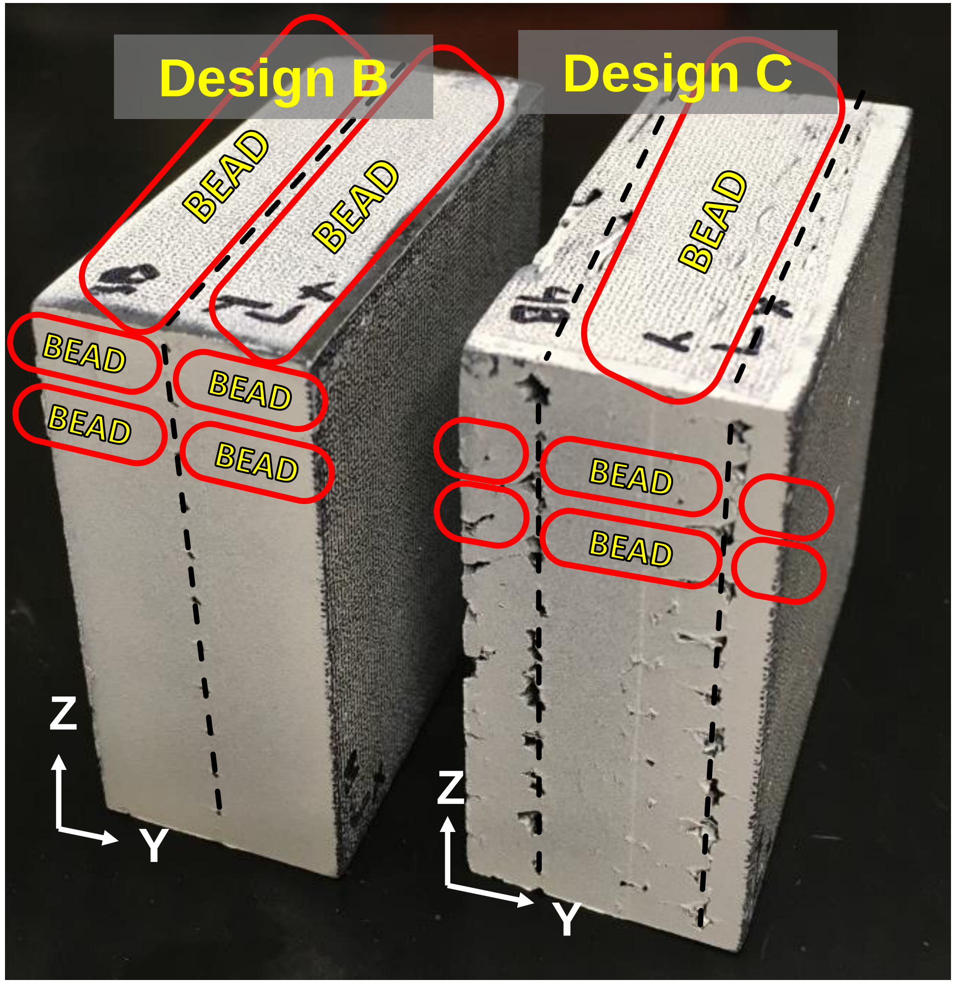


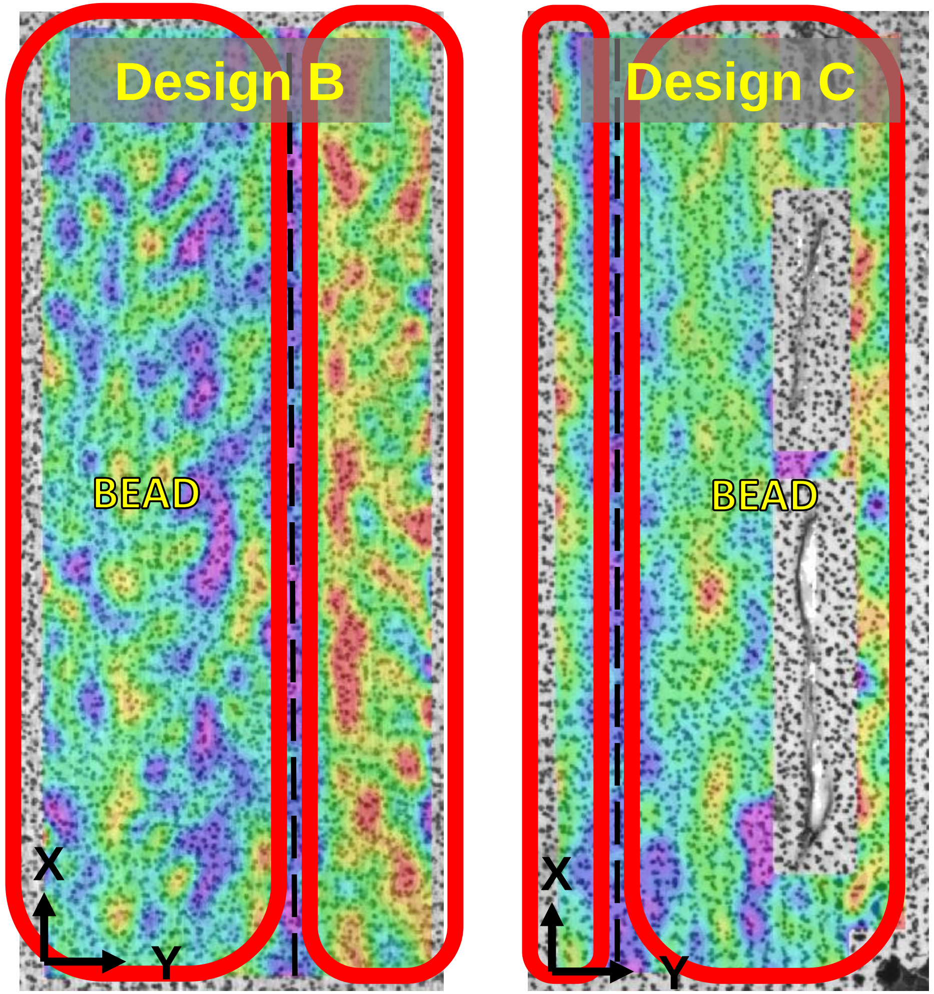
No TMA data was available for Design C

- CTE comparison of each nozzle design shown
- TMA data of same samples overlaid
- The CTE Oven does agree with TMA
- CTE Oven favors outer/inner in some cases

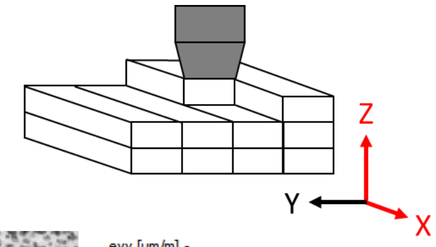
Sample Structure

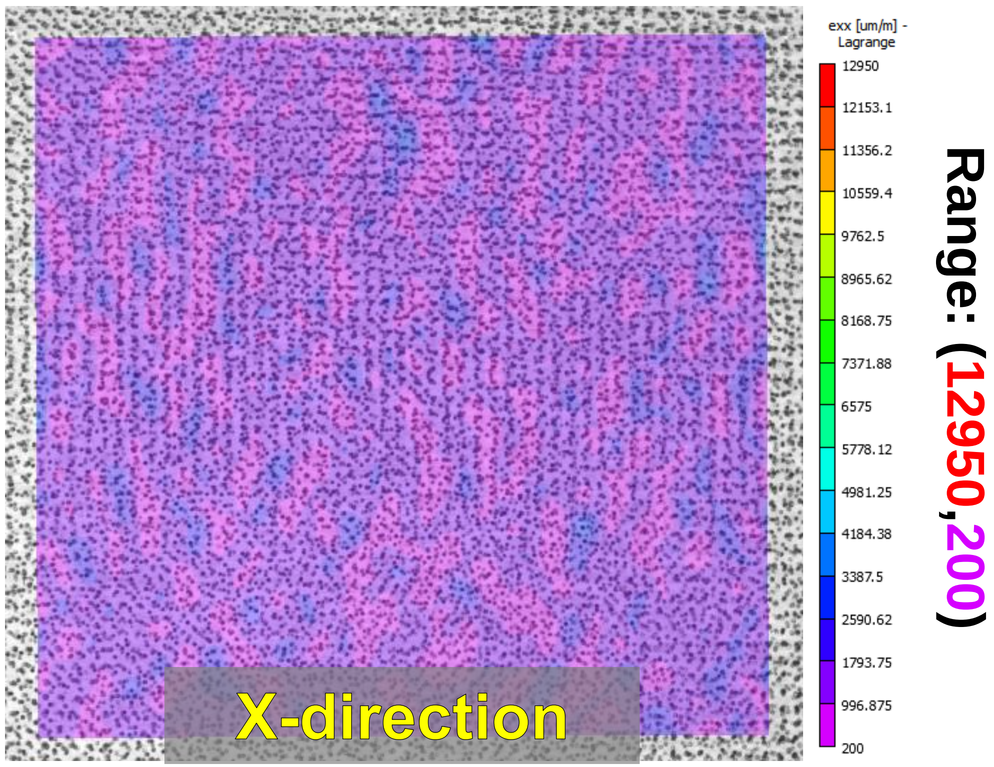


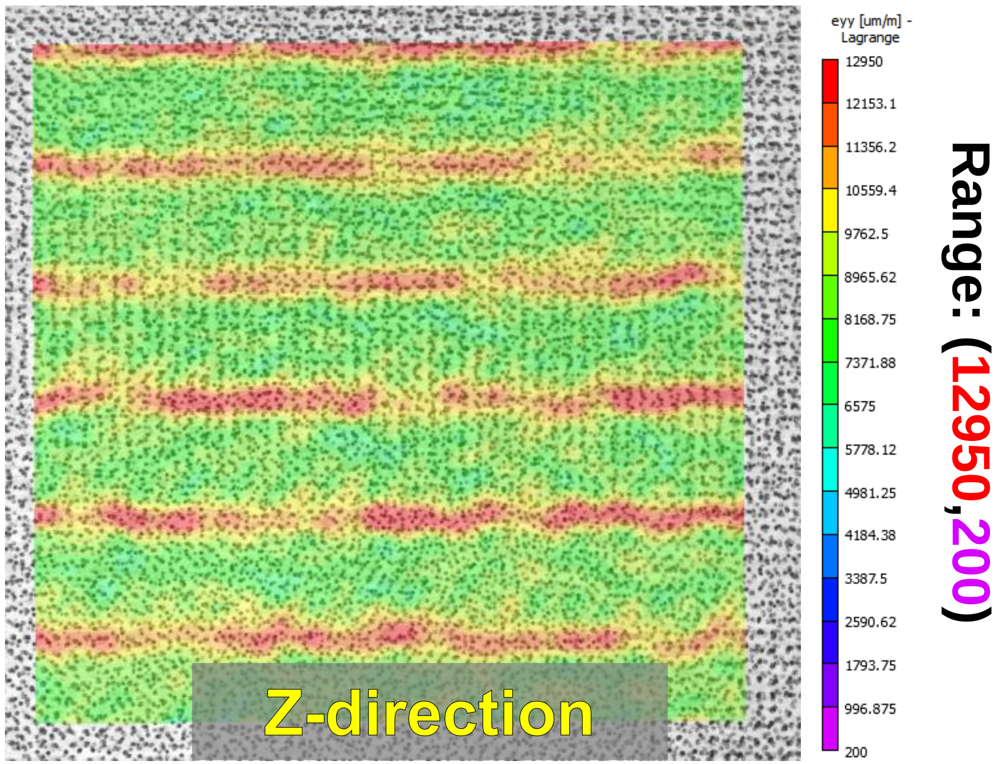




2D Strain Maps – XZ Plane

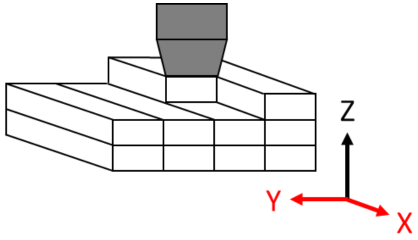


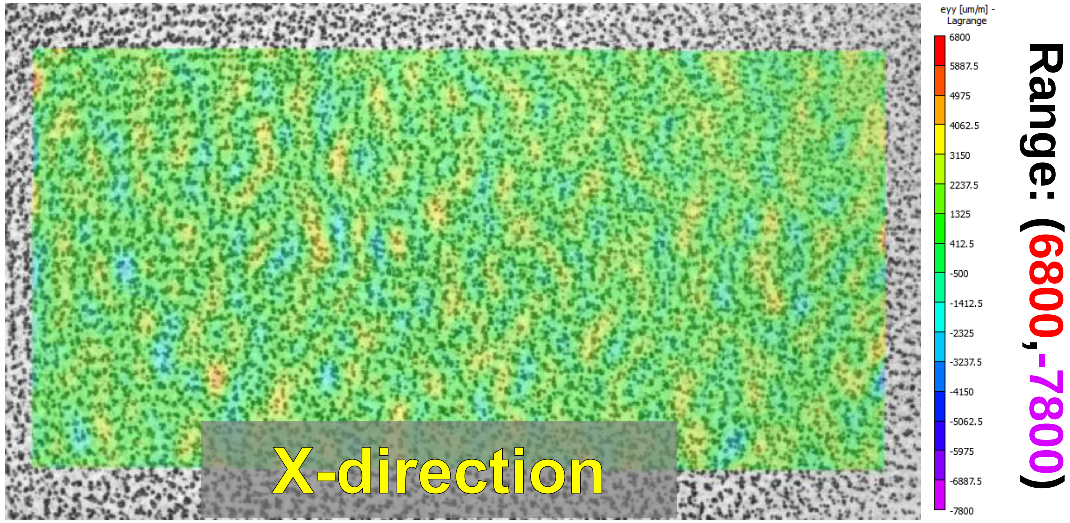


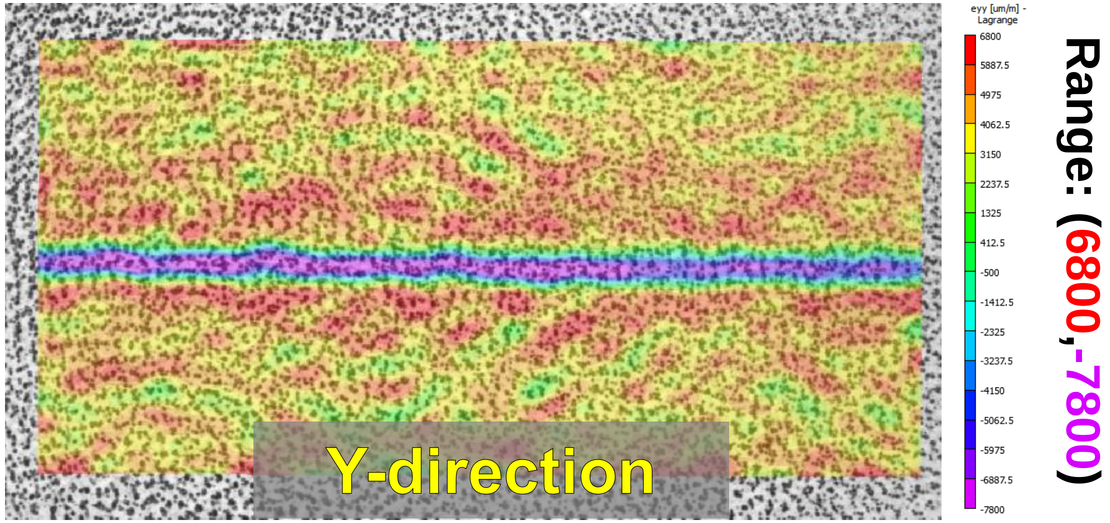


- Stead State Temperature
- Mostly homogenous low strain across the x-direction
- Highest points of strain are between **print layers** in the z-direction as expected from fiber alignment

2D Strain Maps – XY Plane





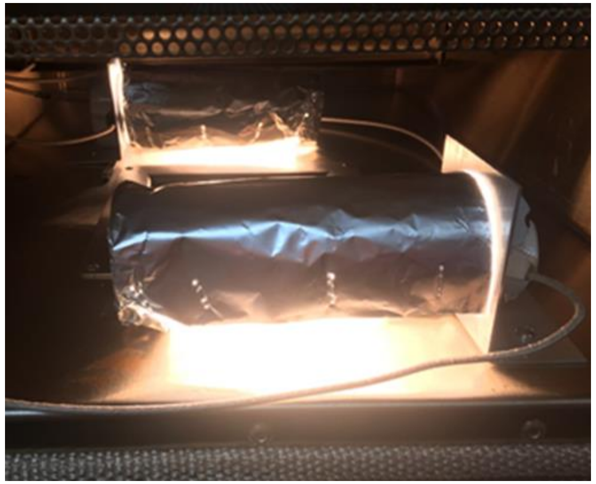


- Stead State Temperature
- Mostly homogenous low strain across the x-direction
- Lowest points of strain are between print beads in the y-direction attempting to “hold the structure together”
- This behavior was expected at **bead interfaces** from fiber alignment

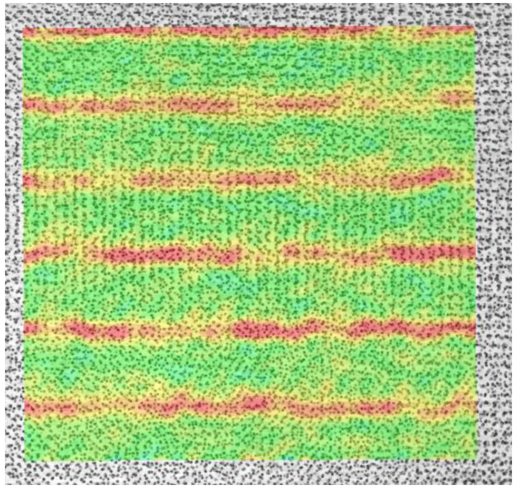
Conclusions

- Successfully improved and calibrated the CTE Oven
- Able to characterize the orthogonal properties of large-scale AM samples made using different parameters

The CTE Oven allows industry to relate the properties of large-scale AM parts to the structure of those parts



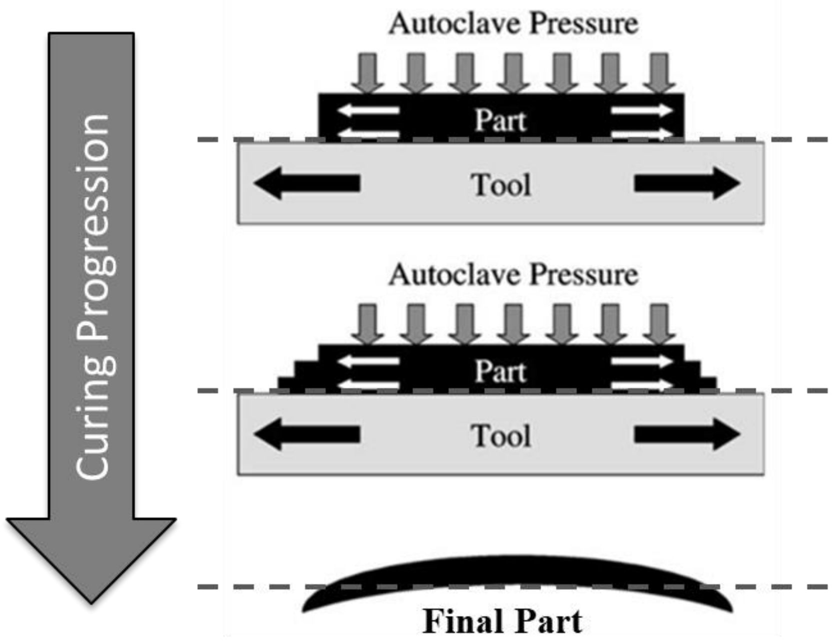
Angled Light Diffusers



XZ Layer Interaction

Future Work!

- Determine the best print parameters for tooling applications
- Develop a print recipe that allows the thermal deformation to be predicted by designers



Tool warping due to poor tool-part interaction [1]

[1] Twigg et al., *Composites Part A: Applied Science and Manufacturing*, Jan. 2004

Acknowledgements

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Oak Ridge National Laboratory

SEAMTN Southeastern Advanced Machine Tools Network

The University of Tennessee Knoxville

Thank you for your time!

Any Questions?