Correlation of ULTEM 9085 Physical, Chemical, and Mechanical Properties

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Acknowledgements

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Motivation, Objective, and Approach

- Motivation
  - Obtain a better understanding of how the properties of AM ULTEM 9085 and its deposition affect the mechanical performance
- Objective
  - Identify abnormal performance of AM ULTEM 9085 qualification and develop theories for mechanical and physical testing
- Approach
  - Review intial statistical analysis and further explore the qualification
  - Development of theories for abnormal ULTEM 9085 performance
  - Print and test AM ULTEM 9085 coupons to explore theories and abnormalities

Topics

1. ULTEM 9085 Qualification
2. Analysis of Qualification
3. Density and Surface Profile Tests
4. Tensile Tests
5. Current Testing

AM ULTEM 9085

- Polyetherimide and polycarbonate amorphous thermoplastic
- Strength-to-weight ratio (480.5lb-in/g)
  - ABS 379.3 lb-in/g
  - PLA 378.3 lb-in/g
  - Nylon 610.9 lb-in/g
- Flame, smoke, and toxicity (FST) characteristics
- Currently used in aerospace and transportation sectors
  - One of only FAA approved!

ULTEM 9085 Qualification Background

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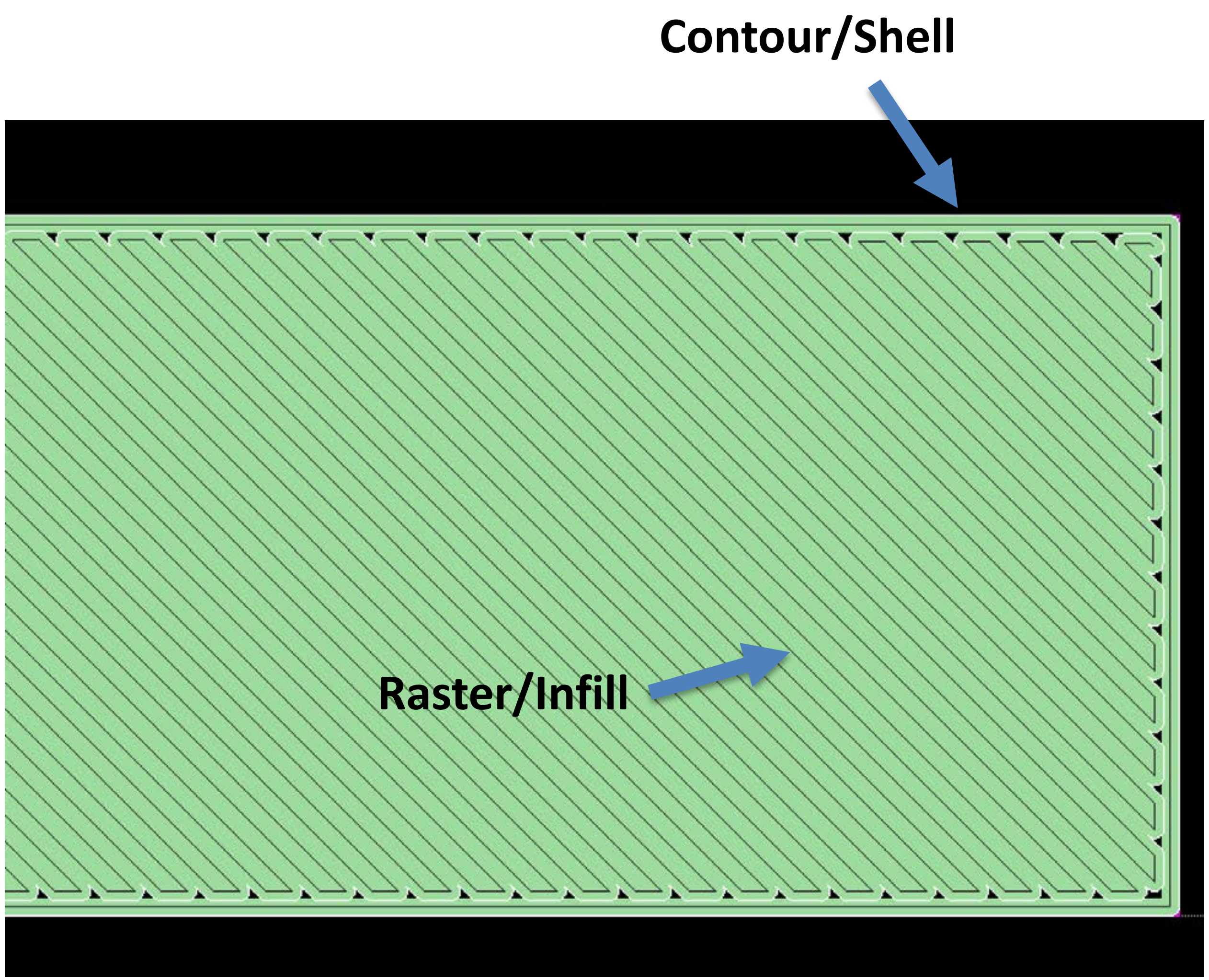
- Planned and tested between 2016-2019 for the first PBAM qualification
- Tested at NIAR
- Analyzed by NCAMP statistician
- Coupons printed on Stratasys F900mc

NIAR®
Wichita State University

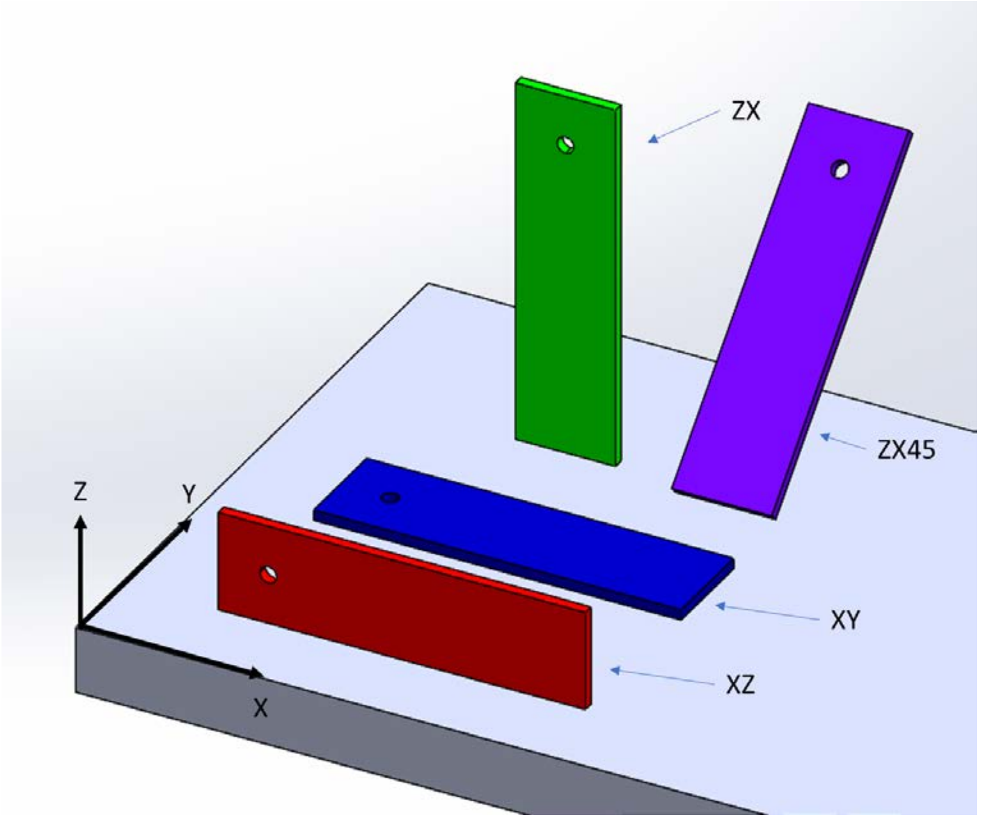
NCAMP
National Center for Advanced Materials Performance

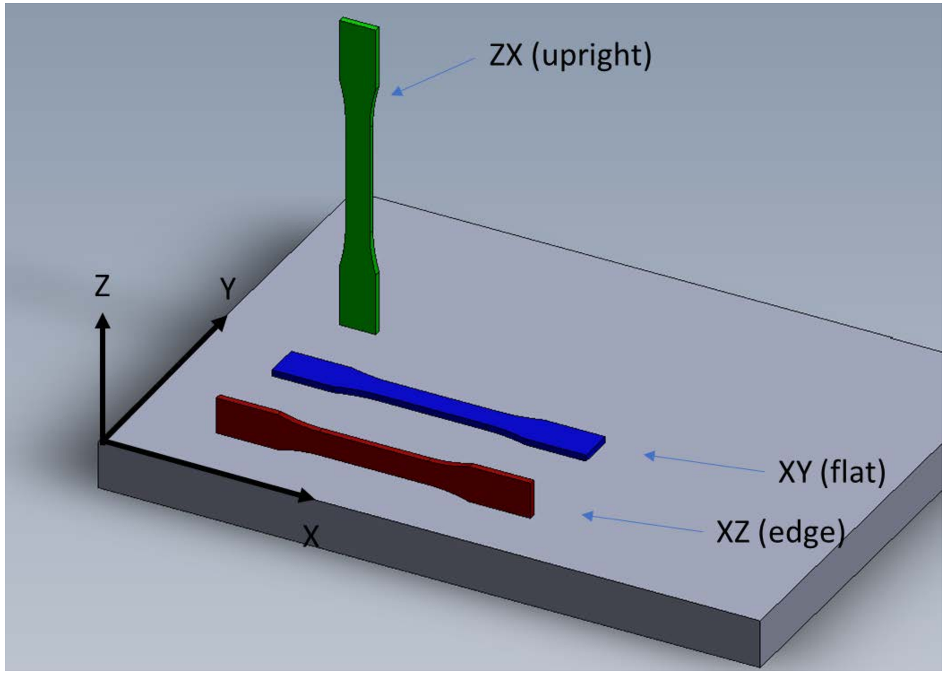
Process Parameter Identification



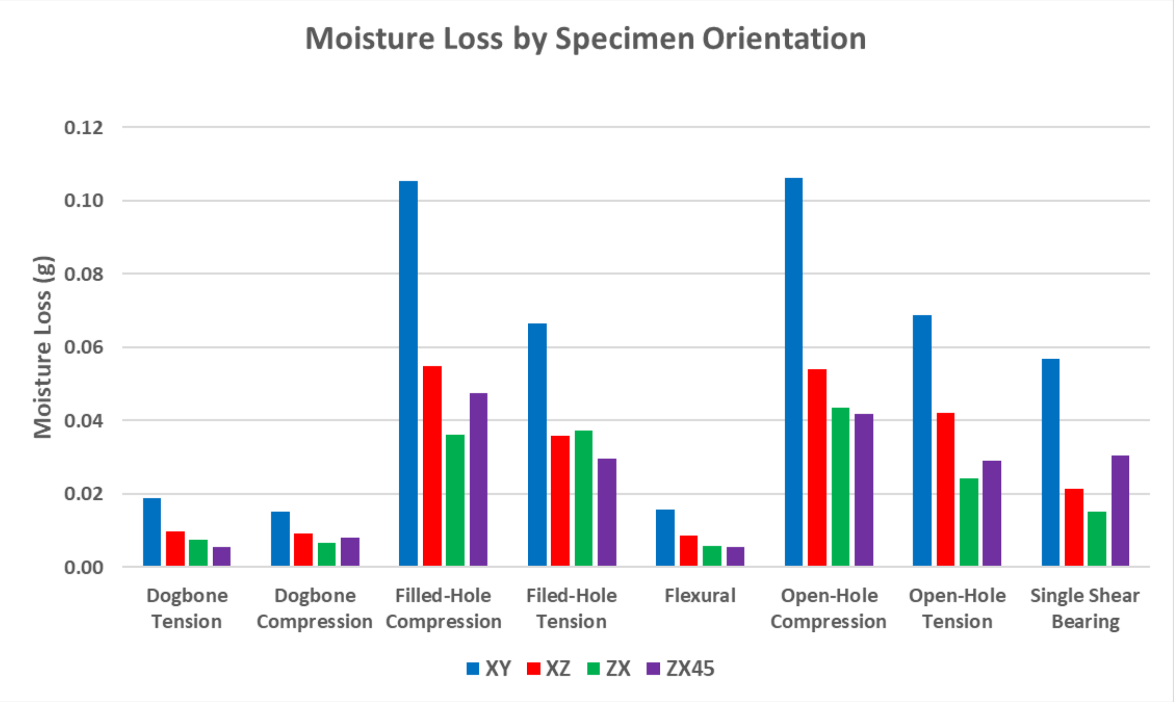
Process Parameter	Default Setting
Part fill style	1 contour / raster
Visible surface style	Normal
Part interior style	Solid
Contour width	0.02”
Part raster width	0.02”
Raster angle	45° (alternating per layer)
Contour to raster air gap	0”
Raster to raster air gap	0”
Extruder temperature	385°C
Chamber temperature	185°C
Bed temperature	185°C
Slice height	0.01”

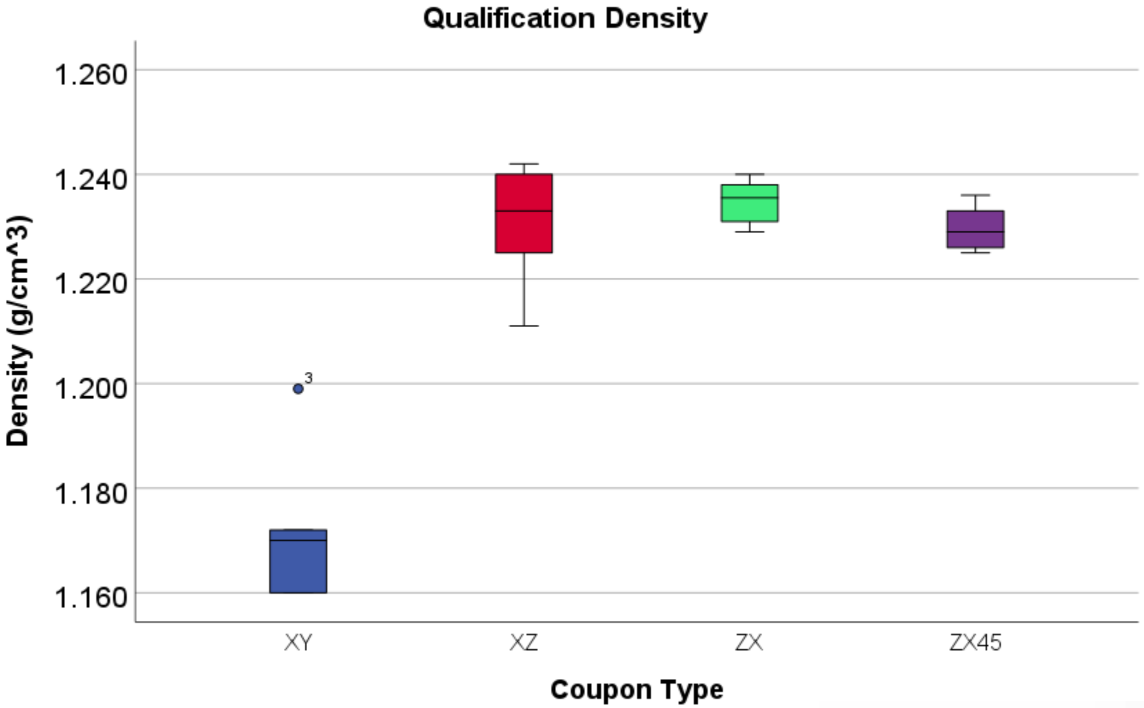
Process Parameter Identification





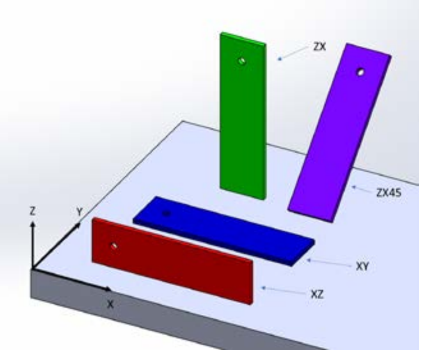
Qualification Exploration Density and Moisture Loss





XY had higher moisture loss and lower density than the other three orientations.

- The higher porosity of the XY allows for more moisture accumulation and therefore higher loss after testing.
- The lower density of the XY attributed to voids formation between alternating raster layers, at contour-to-raster intersections [1], and **incomplete bonding between rasters.**

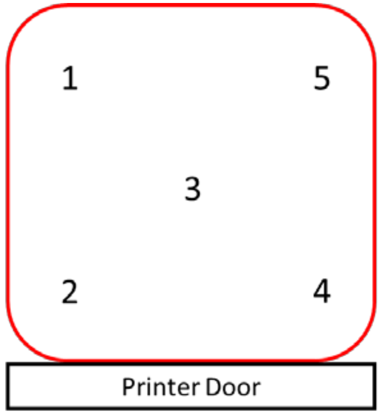


[1] Padovano, E., Galfione, M., Concialdi, P., Lucco, G., & Badini, C. (2020). Mechanical and thermal behavior of ultem® 9085 fabricated by fused-deposition modeling. Applied Sciences (Switzerland), 10(9). https://doi.org/10.3390/app10093170

Density and Surface Profile Testing

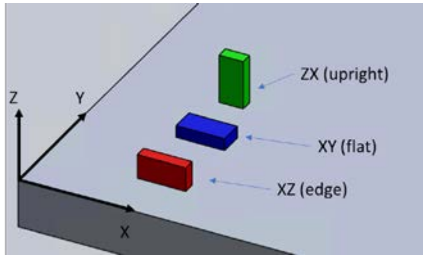
Measure	Analysis (ASTM)	Test Type	Runs (Runs per Machine)	Total Coupons
Density	Relative Density (D792)	ZX, XY, XZ	2 (1)	30
Surface Profile	Profile Scan	ZX, XY, XZ	2 (1)	30

- Density coupons were 1” x 0.5” x 0.25” rectangular blocks
- Gauge coupons all printed to a 0.5” height with the layer area representing the gauge area of the tensile coupons
- Printed coupons with two F900’s at Stratasys (Eden Prairie, MN)
- Used same filament lot for all prints

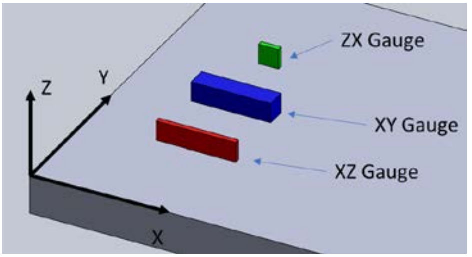


Coupon Build Configuration

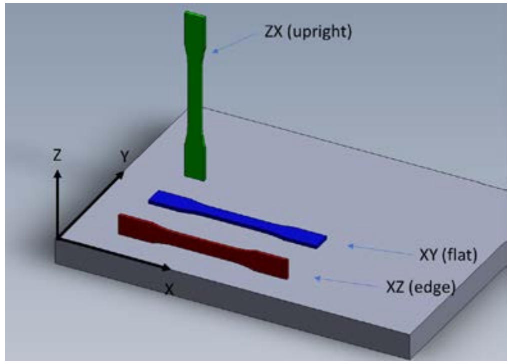
Density



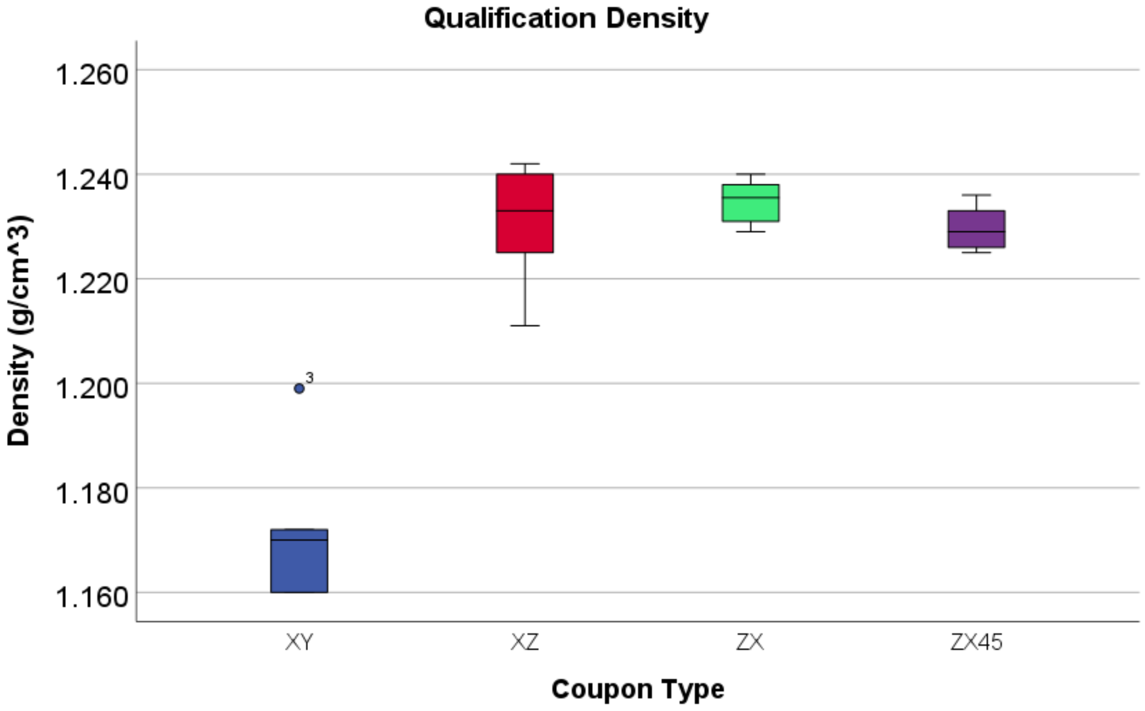
Gauge

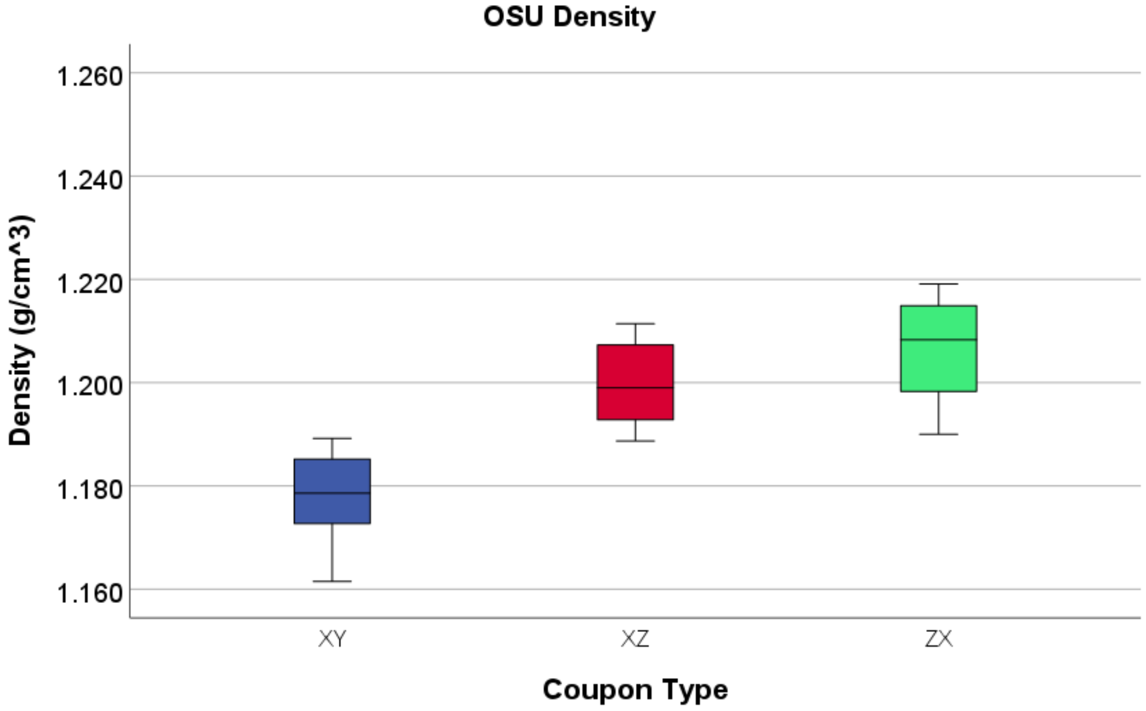


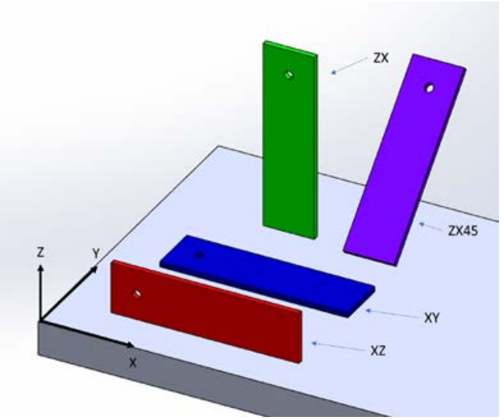
Tensile



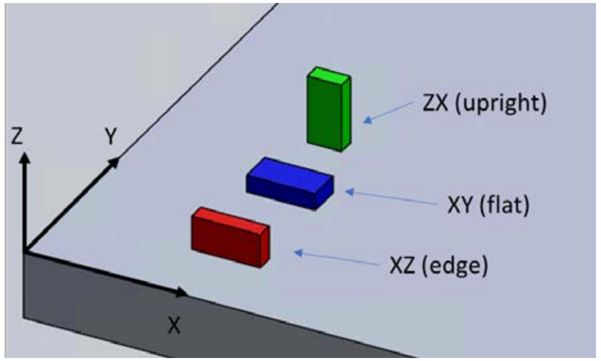
Density Comparison and Summary



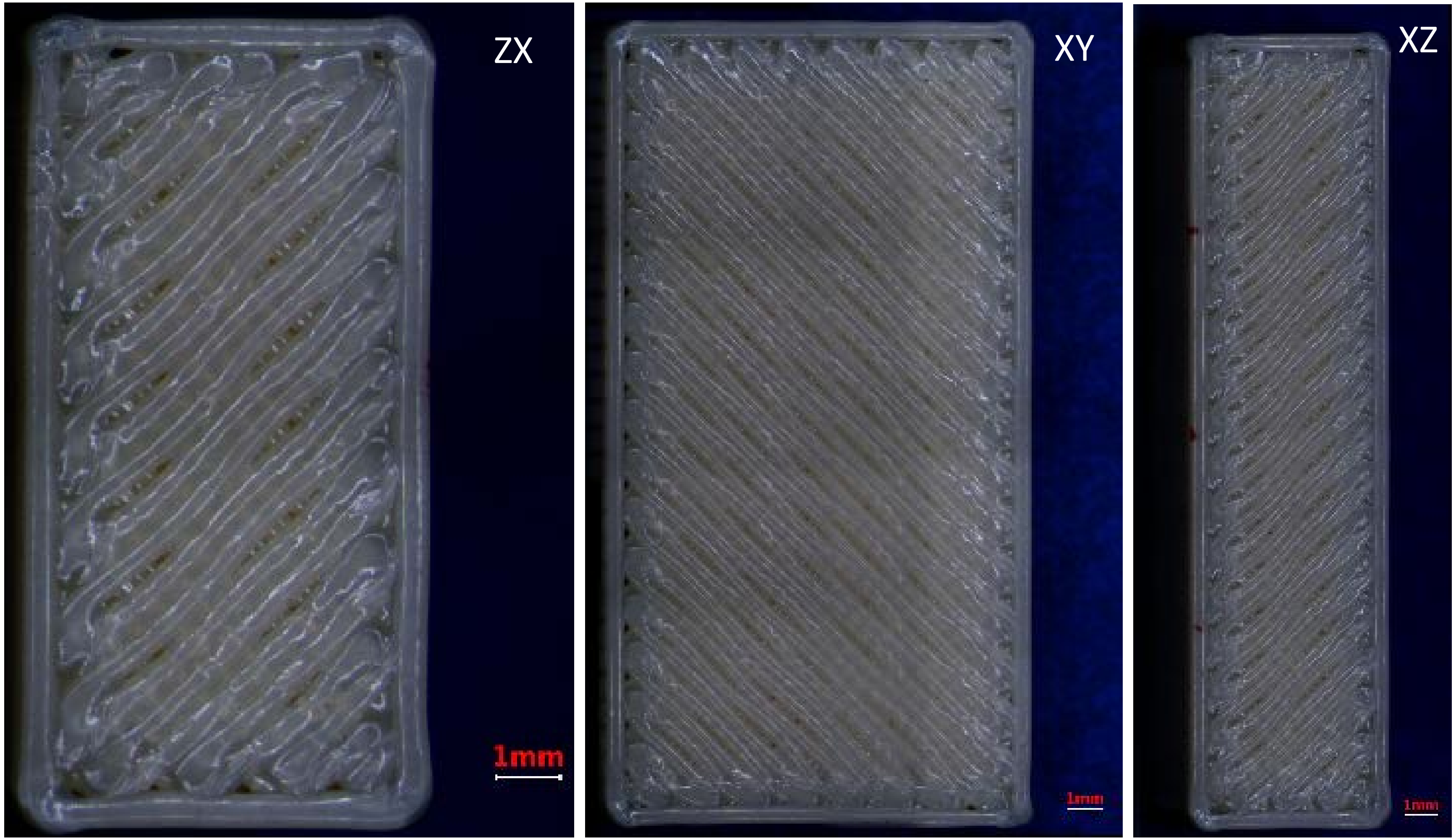


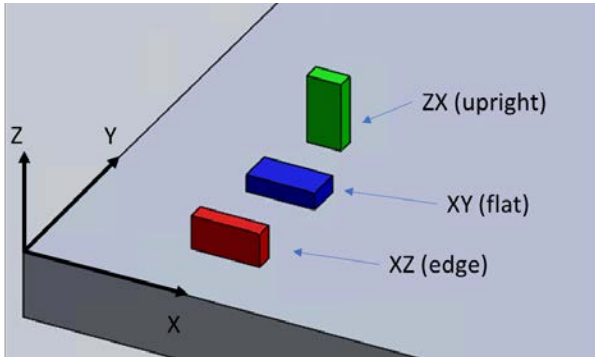


- Sample size:
  - OSU: 10 for each orientation
  - Qualification: 6 for each orientation (1” x 1” sections) cut from SSB coupons after testing
- **Similar trend as qualification, not as extreme differences in density values**



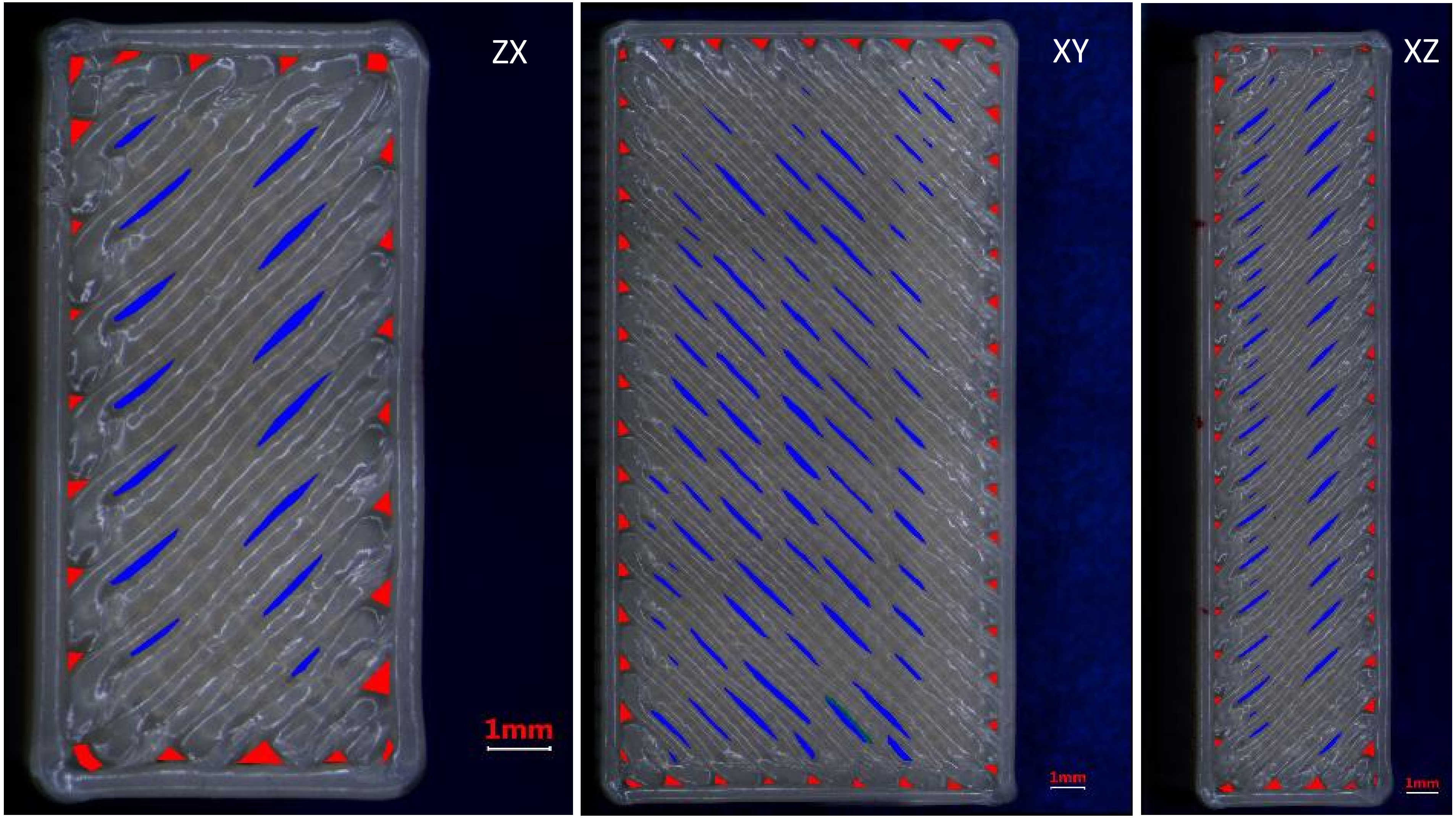
Density Build Layer Microscope Images

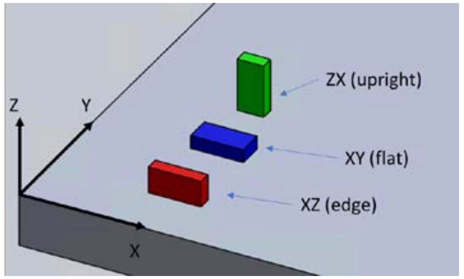




- Light microscope used to capture images of top surface
- Stitched in ImageJ

Surface Voids of Density Coupons





- Blue: Raster-raster (R-R) gaps
- Red: Contour-raster (R-C) gaps

- Top layer is example of what an interior layer looks like after deposition
  - Compare void percentages between coupons

Microscope Void Calculations Density Coupons

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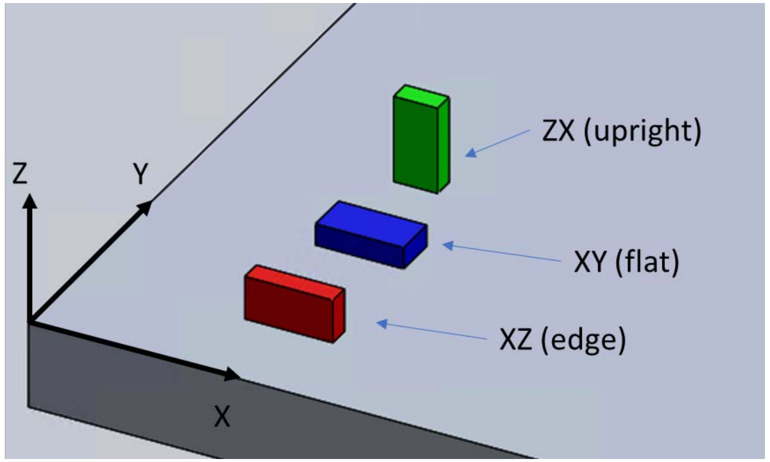
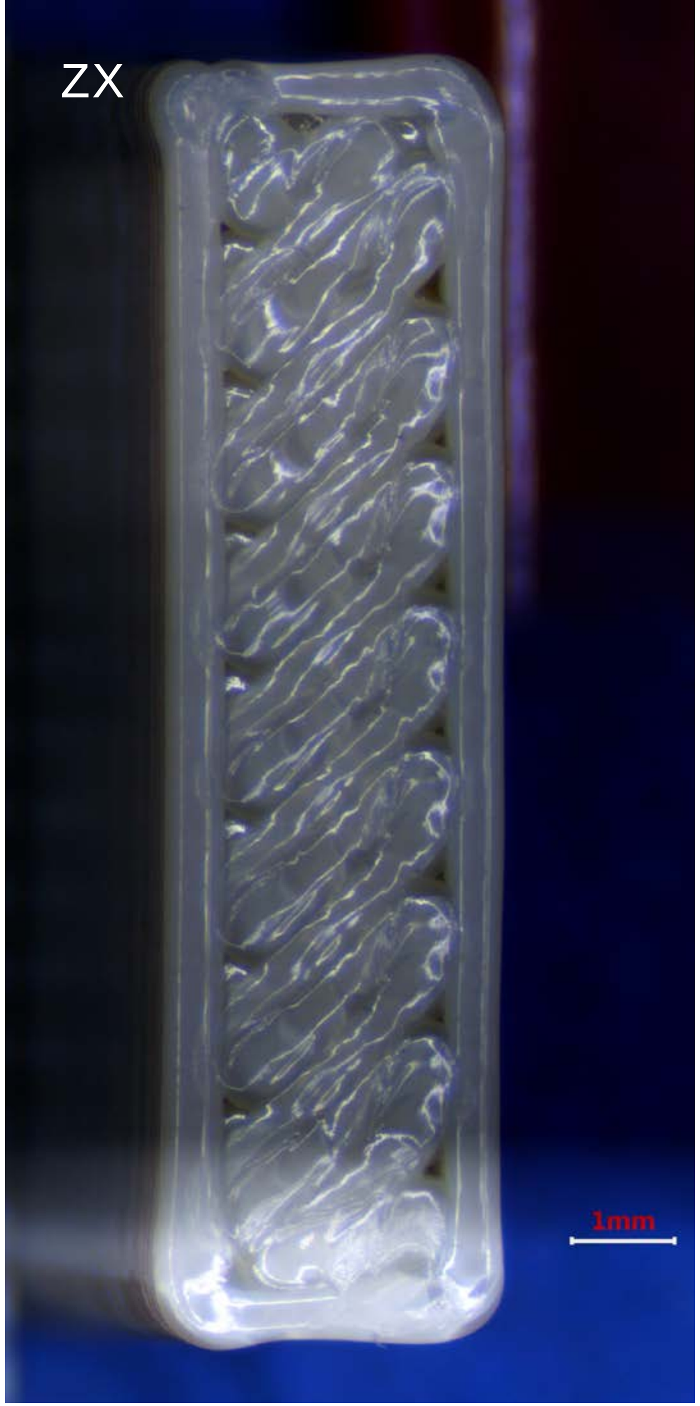
Coupon Type-ID	Theoretical layer area (mm²)	Measured layer area (mm²)	R-R void area (mm²)	C-R void area (mm²)	void area percent of theoretical layer area (%)	void area percent of measured layer area (%)
ZX-21	80.64	79.632	1.958	1.409	4.175	4.228
XZ-20	169.29	156.158	4.615	1.797	3.788	4.106
XY-16	322.58	302.014	12.761	3.459	5.028	5.371

XY has higher void area percentage, specifically attributed to R-R voids





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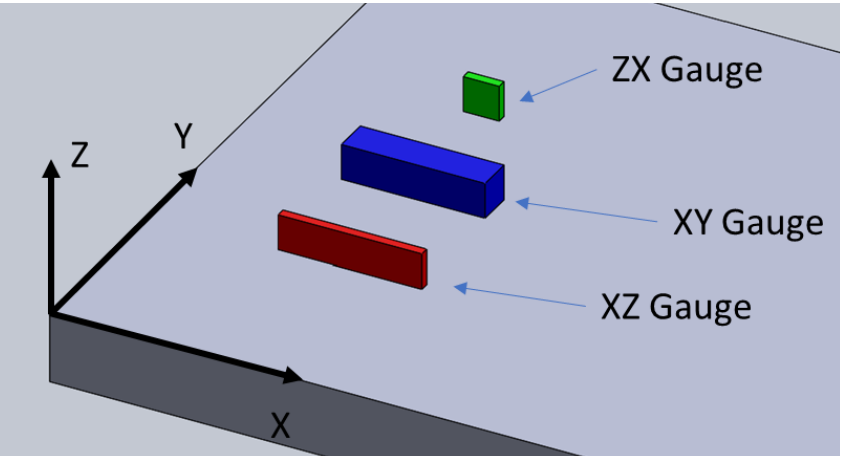
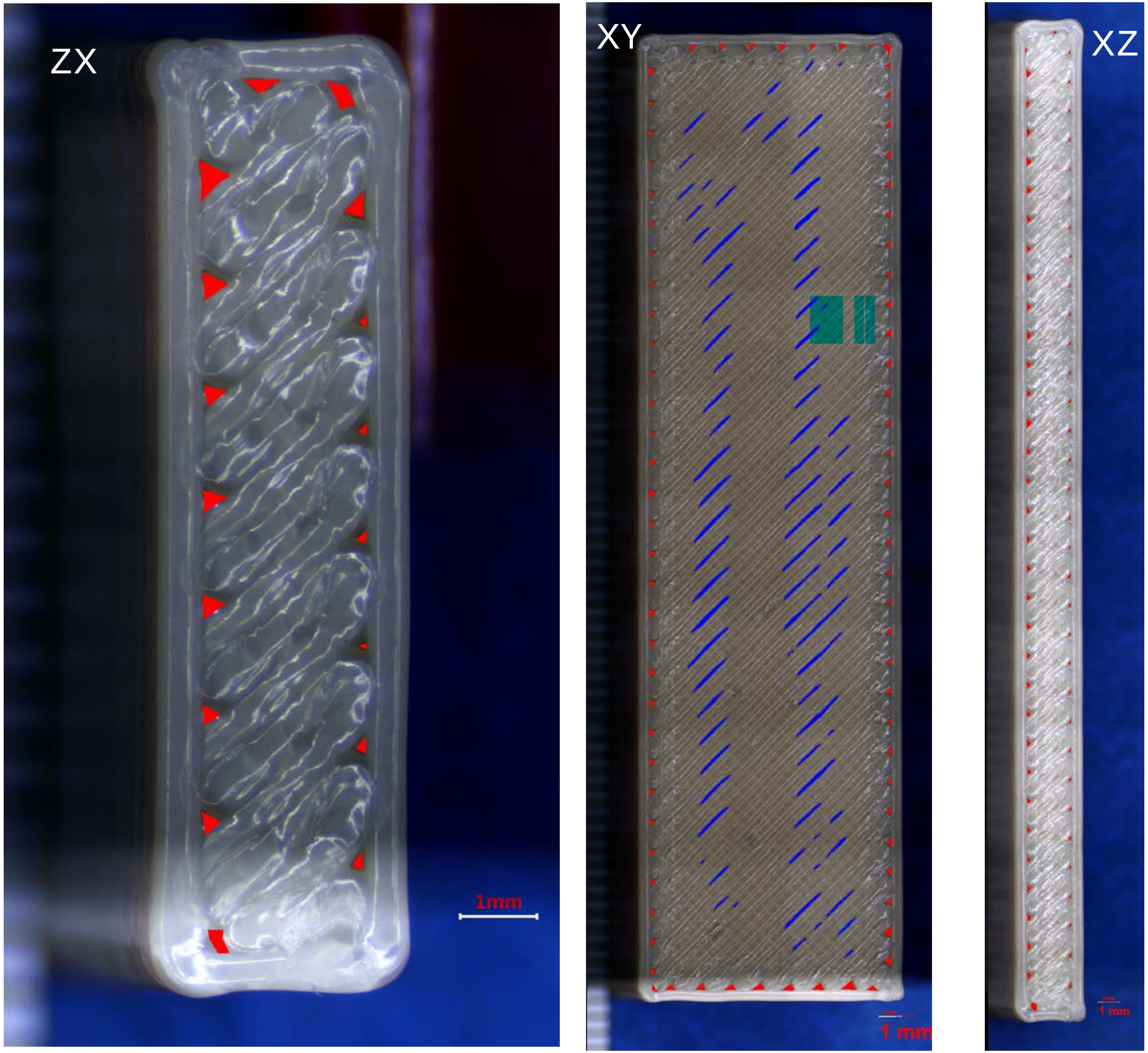
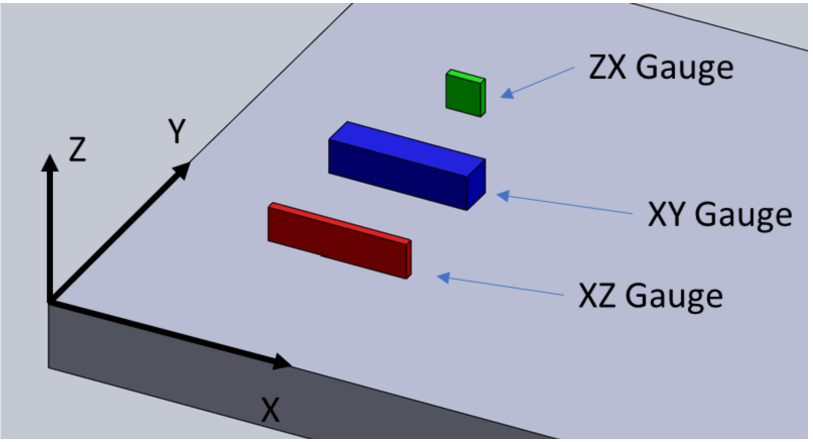


- All coupons same height, differing layer areas



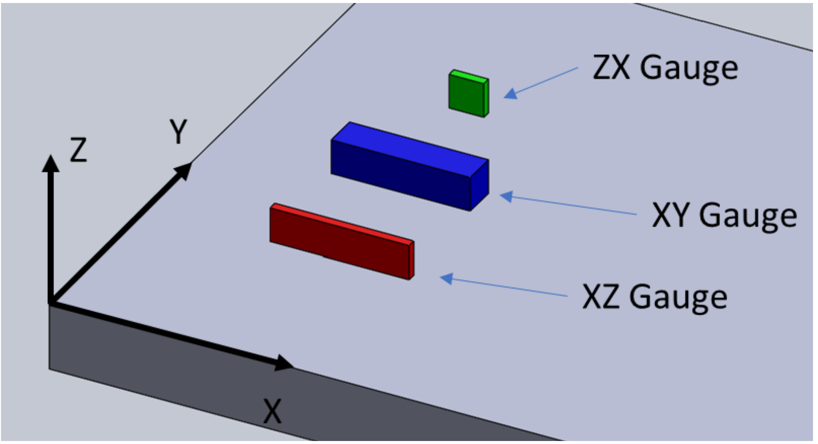


Blue: Raster-raster gaps
Red: Contour-raster gaps

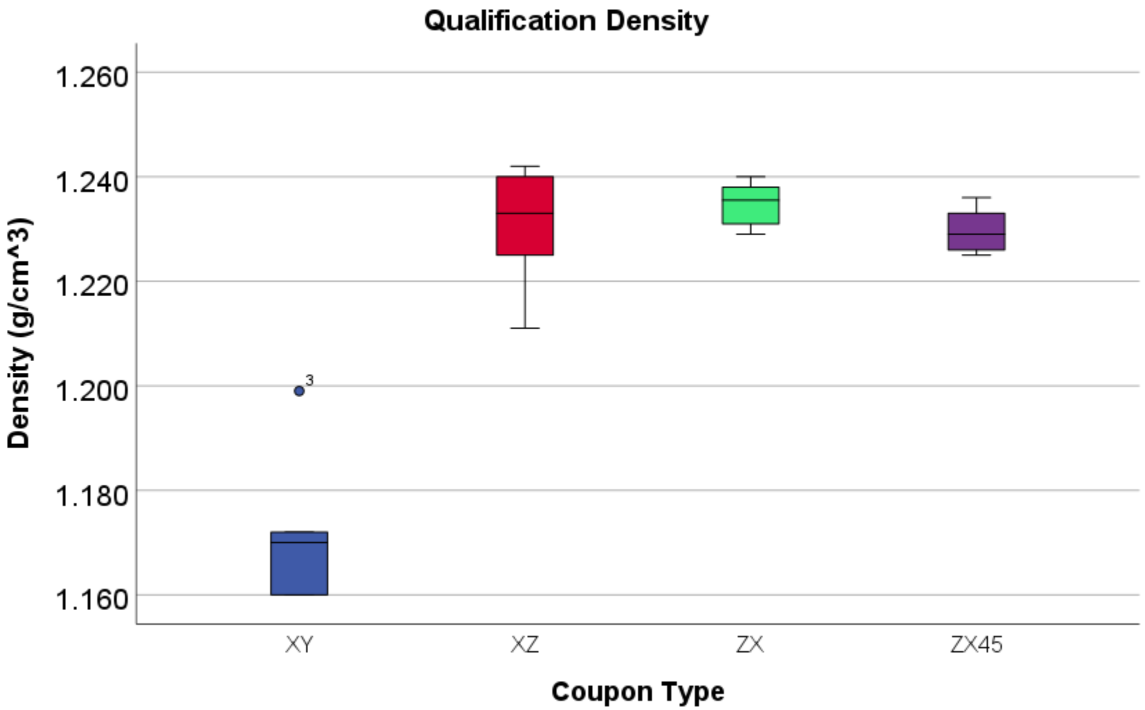
Microscope Void Calculations Gage Coupons

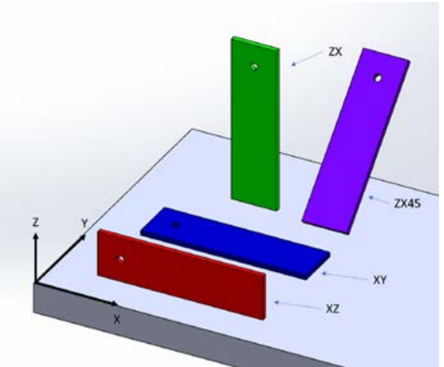
Coupon Type-ID	Theoretical layer area (mm²)	Measured layer area (mm²)	R-R void area (mm²)	C-R void area (mm²)	Void area of theoretical layer area (%)	Void area of measured layer area (%)
ZX Gauge-219	41.9354	40.626	0	0.603	1.438	1.484
XZ Gauge-218	167.742	158.311	0	1.586	0.945	1.002
XY Gauge-217	645.16	555.209	14.806	3.536	2.843	3.304

XY Gauge has higher void area percentage then the other two orientations



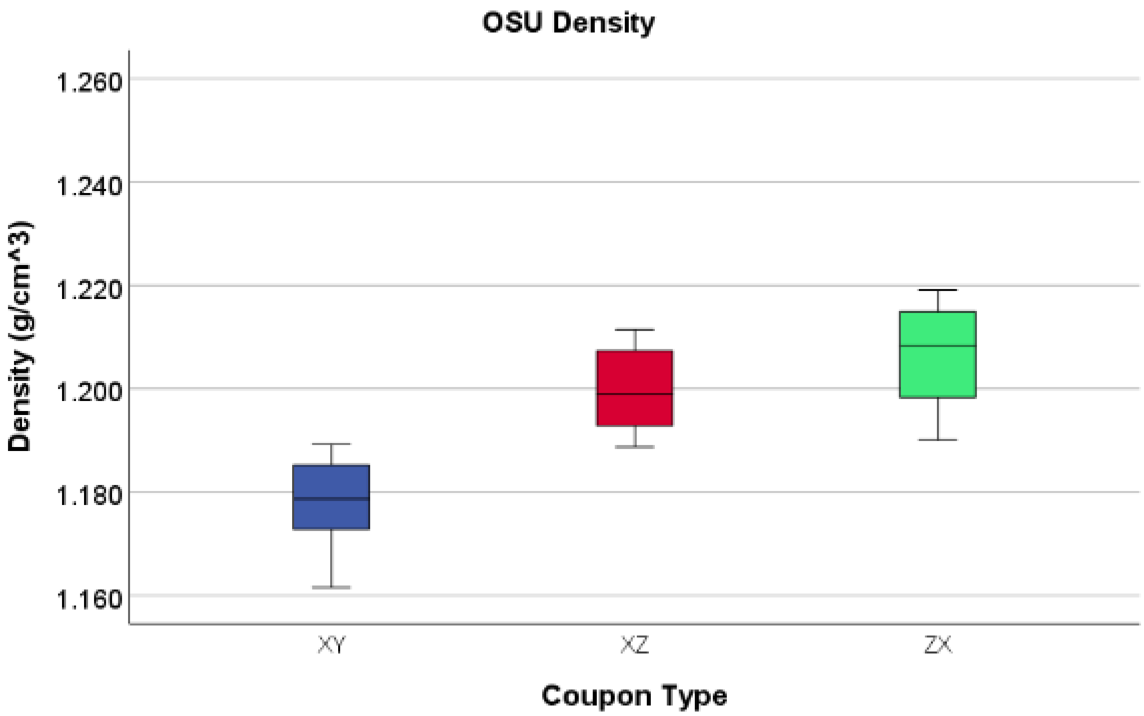
Understanding Qualification Density

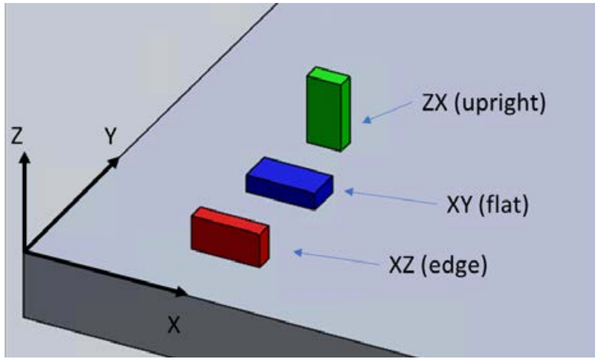




- XZ, ZX, and ZX45 all had a thickness of ~0.16”
  - Short time between raster depositions
  - R-R voids would not be present, higher density
  - XY had a larger build area (5.5” x 1.5”) and more time between raster passes leading to R-R voids and lower density

Understanding OSU Density





- All coupons had a width of 0.25” or higher
- R-R voids present for all coupons
- Though XY still has lower density the difference between coupons is much smaller

Conclusions for Density and Microscope

- Qualification density and OSU density showed similar trends
  - The width (time between raster passes) influenced whether R-R voids were present
  - Coupons with a width of 0.13” did not have R-R voids, but 0.25” or greater coupons did
- R-R voids contributed to the lower density of XY coupons

Abnormal Tensile Performance in Qualification

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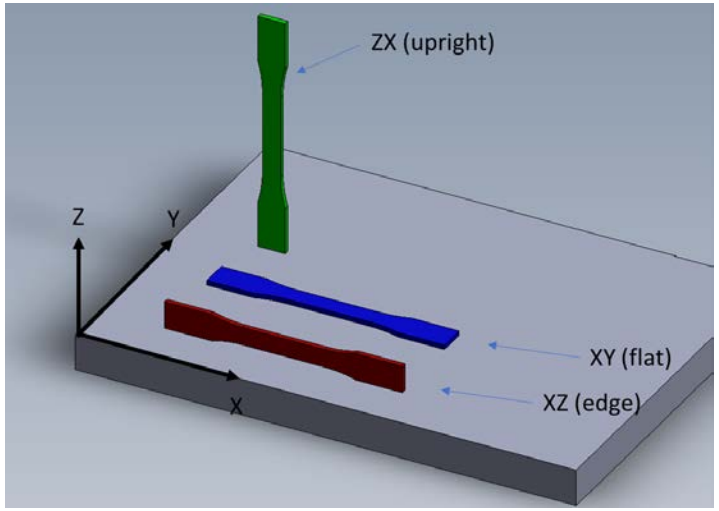
Test	Test Condition	Results	Observation
Dogbone Tension, 0.2% Offset Yield Strength	CTD	XY, ZX, ZX45 combined	**Not expected: XY>ZX,ZX45**
	ETW	XY, ZX, ZX45 combined	**Not expected: XY>ZX,ZX45**
	RTD	XY, ZX combined	**Not expected: XY>ZX**

Wanted to explore and see if results were repeatable



Yield Strength Literature Comparison

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Source	Yield Strength (ksi) for Print Orientations			Replicates per Orientation
	XZ	XY	ZX	
NCAMP (RTD)	6.56	**5.54**	**5.54**	24
[2]	7.94	**6.81**	**4.64**	5
[3]	5.30	**4.32**	**4.10**	4
[4]	4.72	**4.45**	**4.06**	5

Other three studies showed that XY>ZX for yield strength, used ASTM D638

[2] Zaldivar, R. J., Witkin, D. B., McLouth, T., Patel, D. N., Schmitt, K., & Nokes, J. P. (2017). Influence of processing and orientation print effects on the mechanical and thermal behavior of 3D-Printed ULTEM® 9085 Material. Additive Manufacturing, 13, 71–80. https://doi.org/10.1016/J.ADDMA.2016.11.007
[3] Shelton, T. E., Willburn, Z. A., Hartsfield, C. R., Cobb, G. R., Cerri, J. T., & Kemnitz, R. A. (2020). Effects of thermal process parameters on mechanical interlayer strength for additively manufactured Ultem 9085. Polymer Testing, 81. https://doi.org/10.1016/j.polymertesting.2019.106255
[4] Hernandez-Contreras, A., Ruiz-Huerta, L., Caballero-Ruiz, A., Moock, V., & Siller, H. R. (2020). Extended CT void analysis in FDM additive manufacturing components. Materials, 13(17). https://doi.org/10.3390/ma13173831

Tensile Testing

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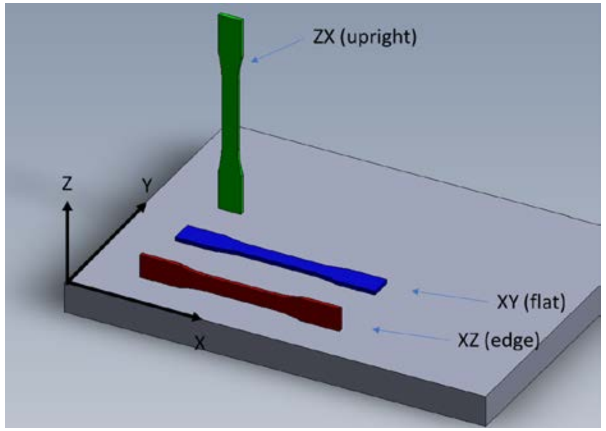
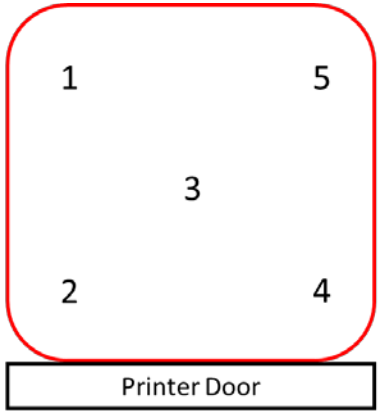
Measure	Analysis (ASTM)	Test Type	Runs (Runs per Machine)	Total Coupons
Strength, 0.2% Yield, Modulus	Tension (D638)	XY1, XZ1, ZX1*	4 (2)	60
		XY0, XZ0, ZX0*	2 (1)	30
		XY3, XZ3, ZX3*	2 (1)	30
		XY5*	2 (1)	30



* The number represents the number of contours

- Printed coupons with two F900's at Stratasys (Eden Prairie, MN)
- Used same filament lot for all prints



Coupon Build Configuration

Modulus Calculation Method

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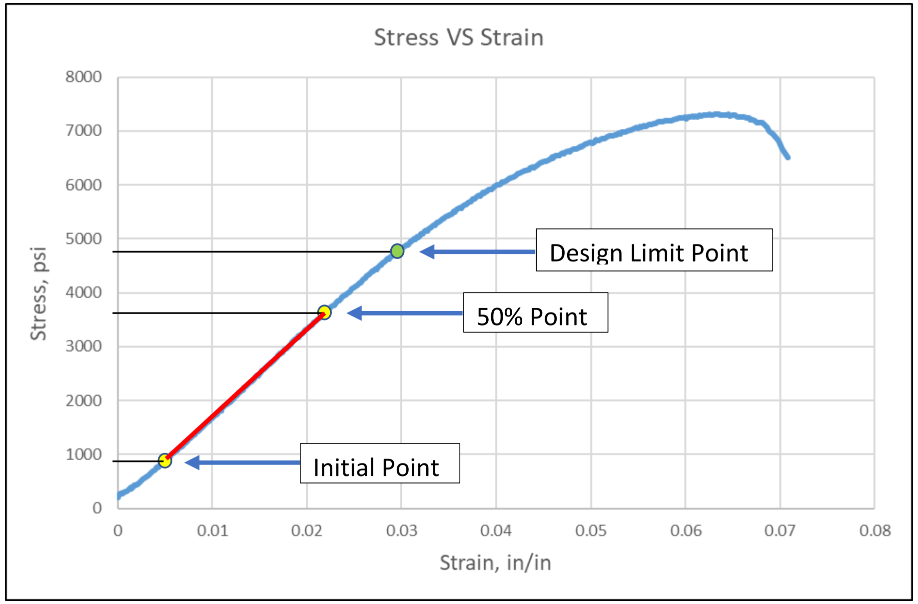
- ASTM D638 (Method 1)
  - Linear section of stress curve
  - Qualification used 1000-3000 με
- CMH-17 (Method 2)
  - Point at the 10-15% to 40-50% of tensile strength
  - Avoids the "toe" region common with AM polymers
- **Used both methods to see if results could be repeated from qualification**



Courtesy of Rick Cole

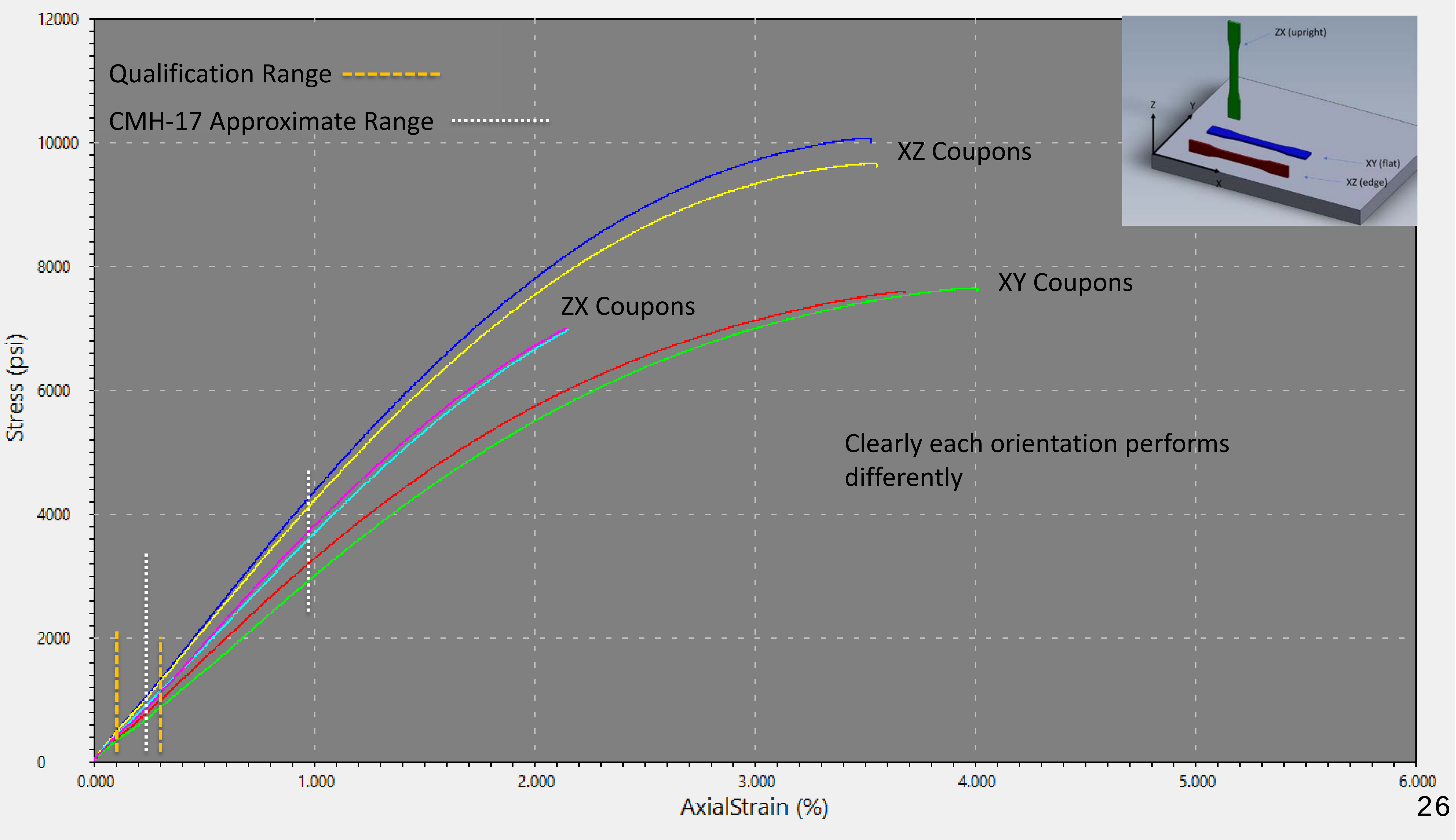
1 Contour Results

Data Source	Tensile Strength (ksi)		
	XZ	XY	ZX
Qual (RTD)	9.977	8.827	8.214
OSU	9.819	7.640	6.839

Data Source	Modulus Method	Modulus (Msi)		
		XZ	XY	ZX
Qual (RTD)	1	0.377	0.337	0.347
OSU	1	0.433	0.329	0.398
OSU	2	0.431	0.345	0.396

Data Source	Modulus Method	0.2% Offset Yield Strength (ksi)		
		XZ	XY	ZX
Qual (RTD)	1	6.561	5.544	5.540
OSU	1	7.498	5.753	6.089
OSU	2	7.541	5.592	6.466

- Using the Qualification method (1000-3000 με) XY and ZX were not significantly different
- ZX>XY, not expected


Qualification Range
CMH-17 Approximate Range
XZ Coupons
XY Coupons
ZX Coupons
Clearly each orientation performs differently
ZX (upright)
XY (flat)
XZ (edge)
Z
Y
X
Stress (psi)
AxialStrain (%)
0
2000
4000
6000
8000
10000
12000
0.000
1.000
2.000
3.000
4.000
5.000
6.000

XZ Contour Comparisons

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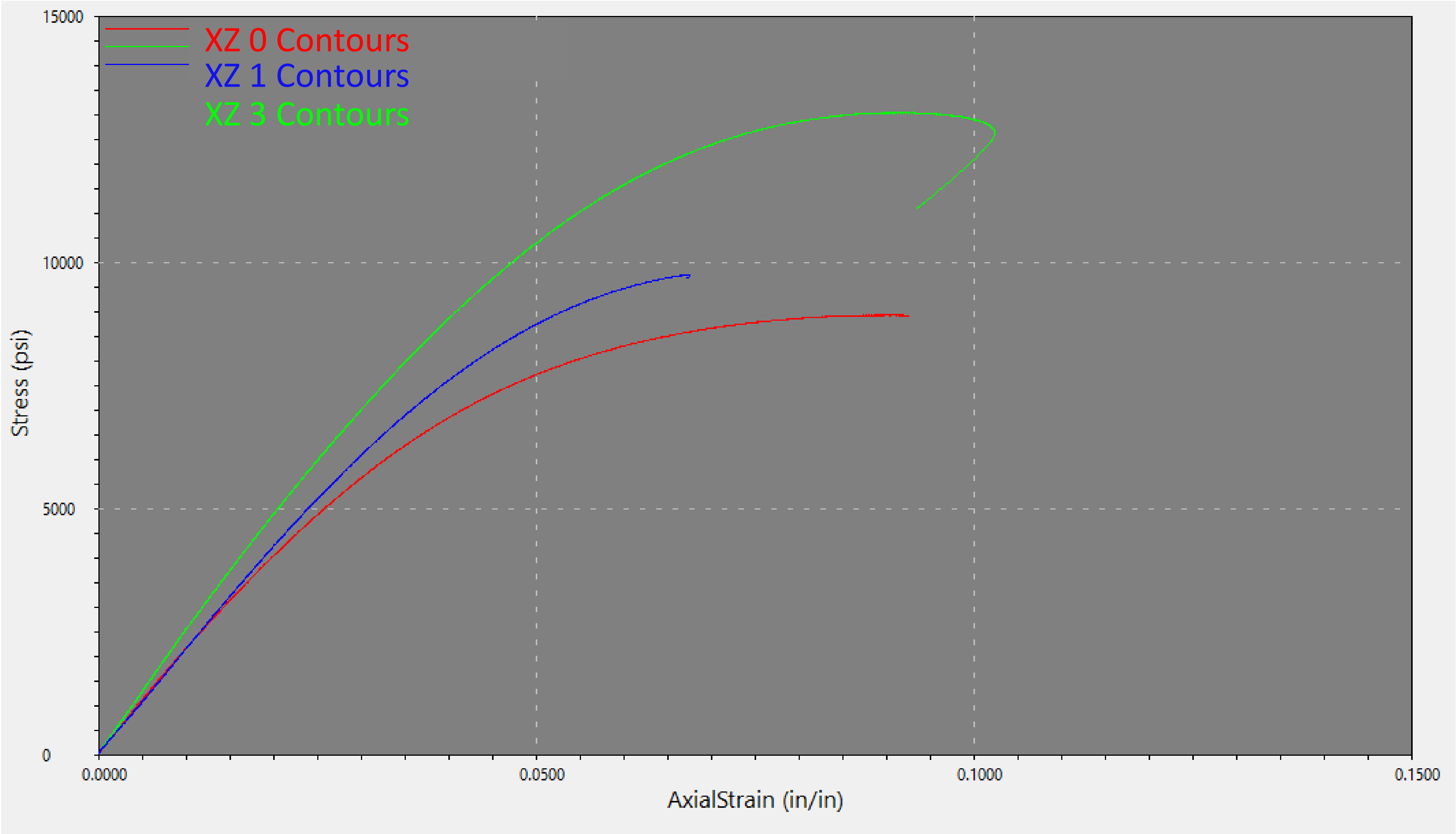

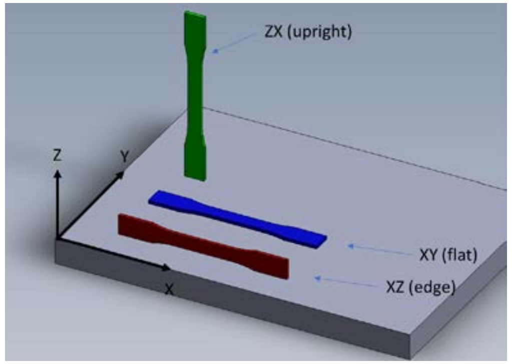

XY Contour Comparisons

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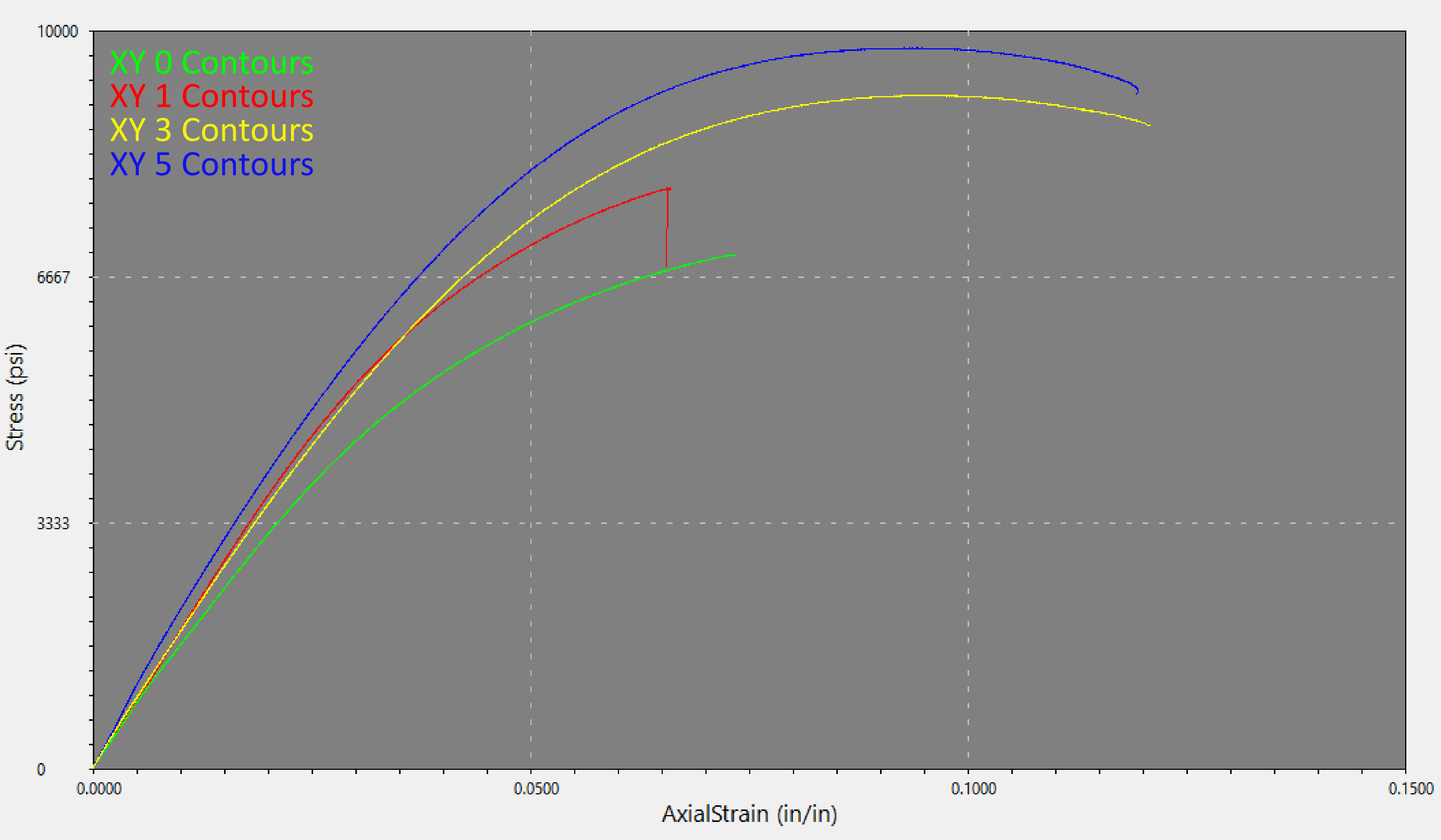
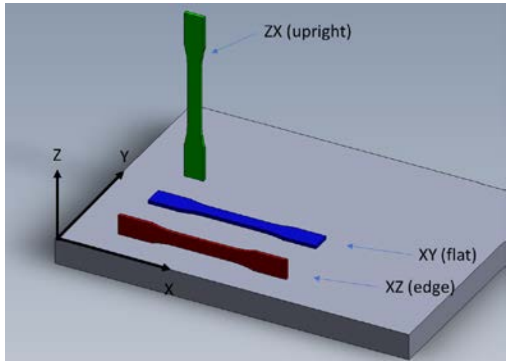
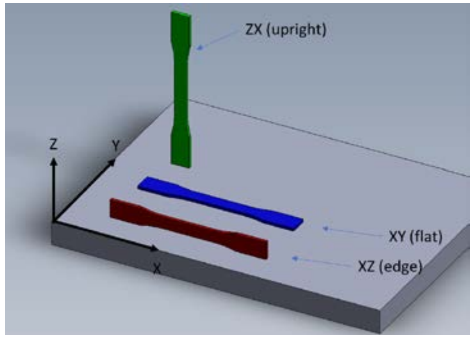




Tensile Summary

Contour Number	Build Orientation	0.2% Yield Strength (ksi)	Tensile Strength (ksi)	Modulus (Msi)
0	XY	4.784	6.513	0.306
	XZ	6.678	9.201	0.385
	ZX	6.328	7.710	0.384
1	XY	5.592	7.640	0.345
	XZ	7.541	9.819	0.431
	ZX	6.466	6.839	0.396
3	XY	6.553	9.187	0.361
	XZ	9.614	13.206	0.472
	ZX	6.816	8.089	0.414
5	XY	7.023	9.833	0.385



- ZX Results
  - 0.2% offset not statistically different between 0 and 1 contours
  - Tensile strength not statistically different between 0 and 3 contours
  - Modulus not statistically different between 0 and 1 contours
- **For the XZ and XY orientations all tensile properties increase as the number of contours increased in the direction parallel to the load**

Tensile Contour Conclusion

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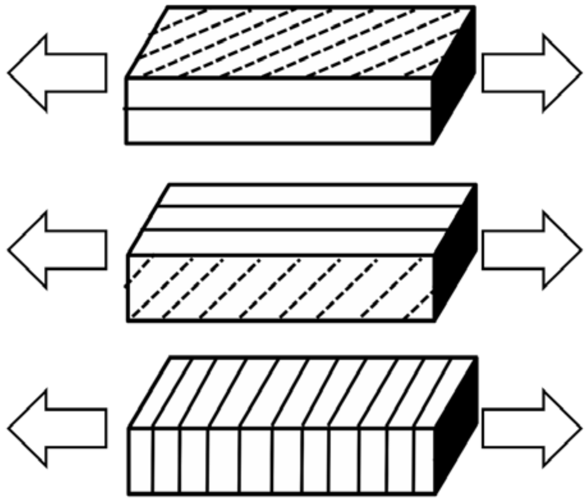
- The number of contours increased the mechanical properties of XY and XZ
  - More extruded lines parallel to direction of load
- ZX was not greatly affected by increased number of contours
  - Pulling between interlayer bonds



Explanation of Tensile Performance XY

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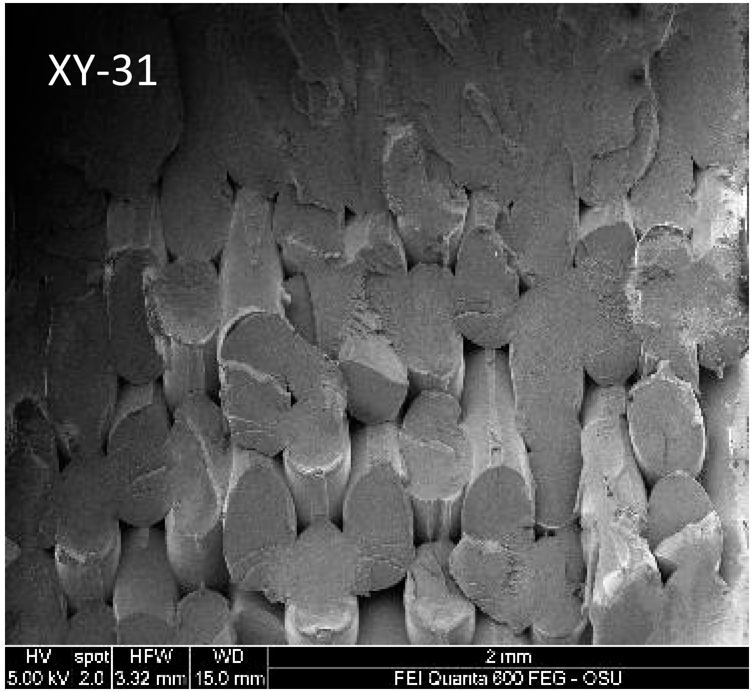
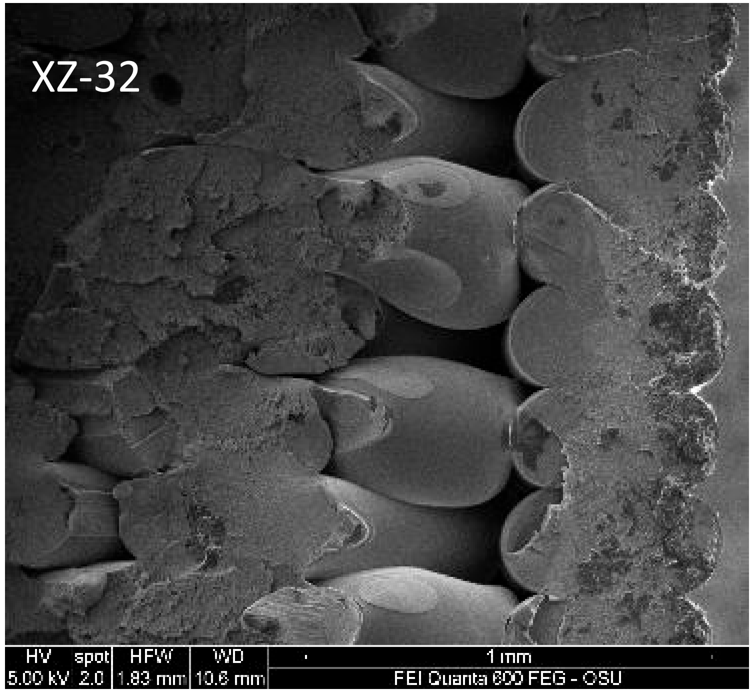
- Incomplete bonding of rasters/less contours led to reduced mechanical properties



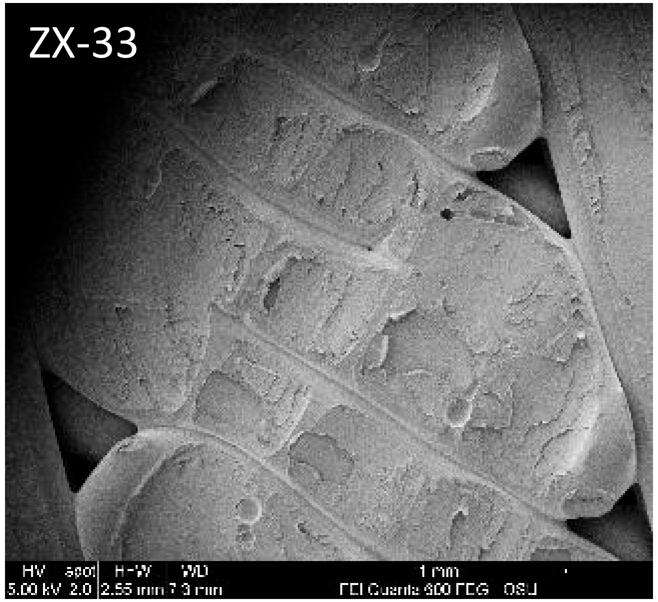
Explanation of Tensile Performance XZ

- Extensive intralayer raster bonding and higher number of contours led to highest mechanical properties



Explanation of Tensile Performance ZX

- ZX had lateral failures pulling between interlayer bonds



Current Testing

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- Conducting v-notch shear, compression, and single shear bearing testing with different coupon geometries
- Developing a machine learning module to output print time, print weight, and stress strain curve based on input process parameters

Questions and comments are encouraged

Thank you!