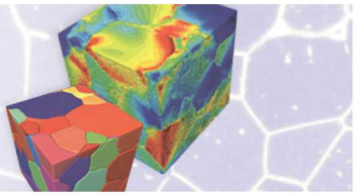
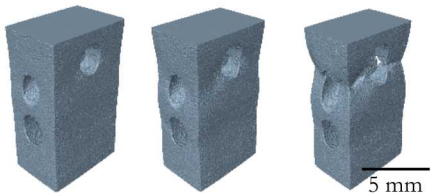
SAND2018-6157C

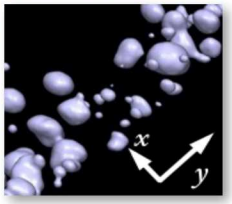
The 4th International Congress on 3DMS 3D Materials Science 2018

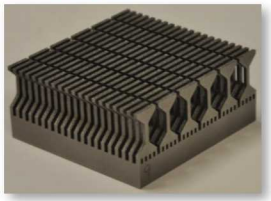


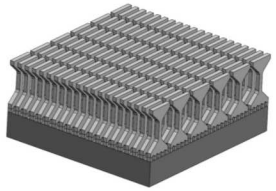
Sandia National Laboratories

AGGREGATE PRESENCE & IMPACT OF 3D DEFECT POPULATIONS IN AM STAINLESS STEEL









PRESENTED BY

Jonathan D. Madison

Thomas Ivanoff, Laura Swiler, Stephanie DeJong, Brad Boyce, Bradley Jared, Jeffrey Rodelas, Bradley Salzbrenner

U.S. DEPARTMENT OF ENERGY NNSA

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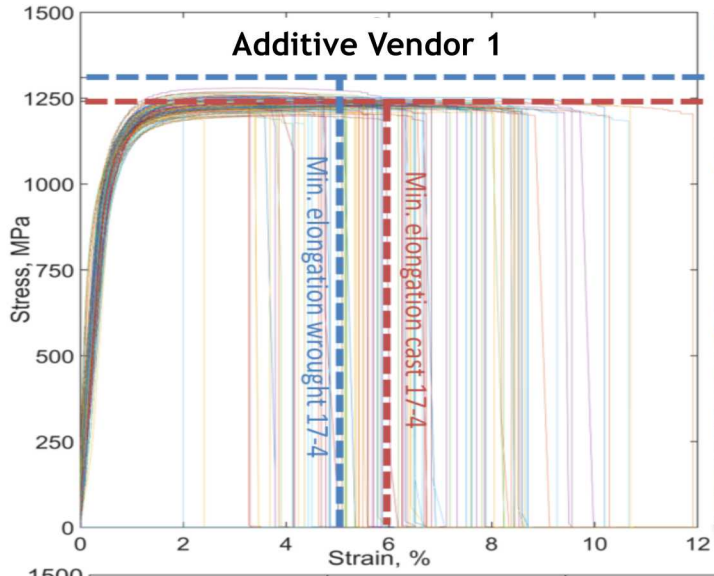
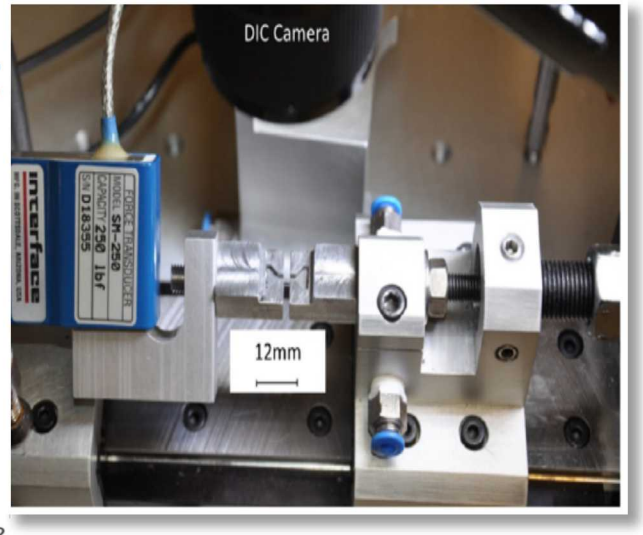
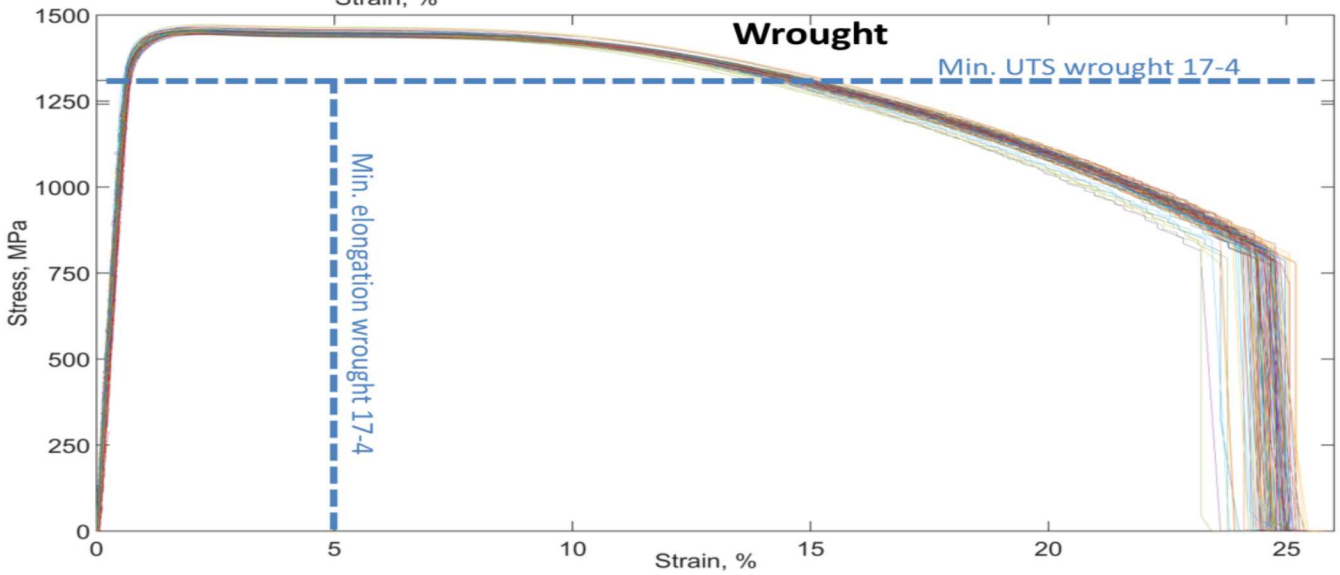
Outline

- **Additive: A Motivating & Challenging Technology**
- **Image Segmentation Toolbox**
- **3D Quantification Metrics**
- **3 On-going Studies in Additive**
  - *In-Situ Defect Detection for Powder Bed Fusion*
    - in-situ characterization
    - global post mortem process : structure relationship
  - *High-Throughput Mechanical Testing*
    - ex-situ characterization
    - global post mortem structure : properties relationship
  - *Sandia's 3rd Fracture Challenge*
    - in-situ characterization
    - local post mortem structure : performance relationship
- **Summary**

Additive Manufacturing – A Motivating and Challenging Technology

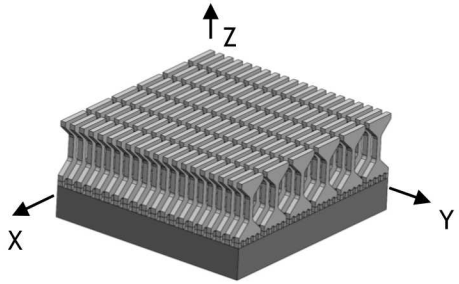


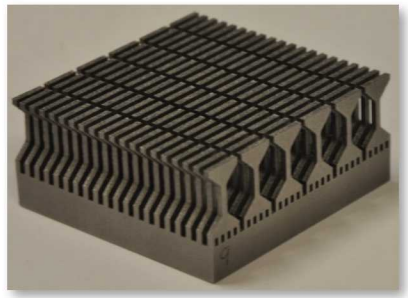




Generation 1 HTT AM Geometry

6 columns x 20 rows
120 tensile dog bones per build
1 x 1 mm tensile gage section
Externally fabricated by vendor



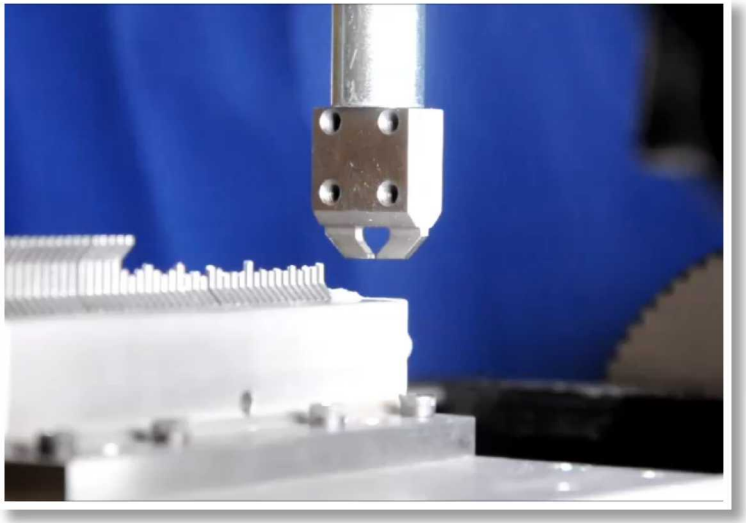


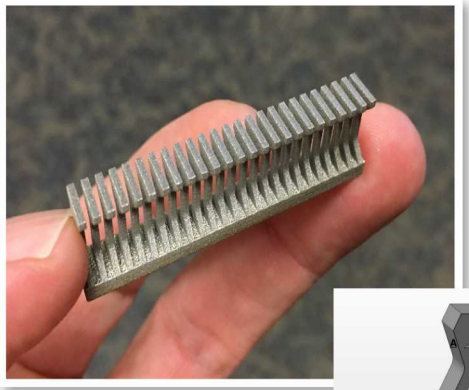
AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

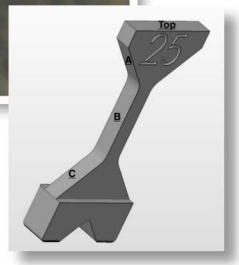
*Salzbrenner, et al., **J. Mat. Proc. & Tech.** vol. 241 (2017) pp. 1-12*

B. Boyce, B. Salzbrenner

Additive Manufacturing – A Motivating and Challenging Technology

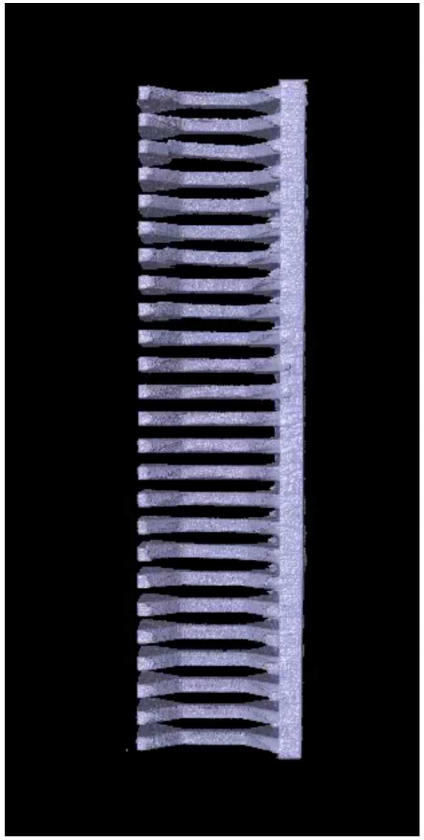


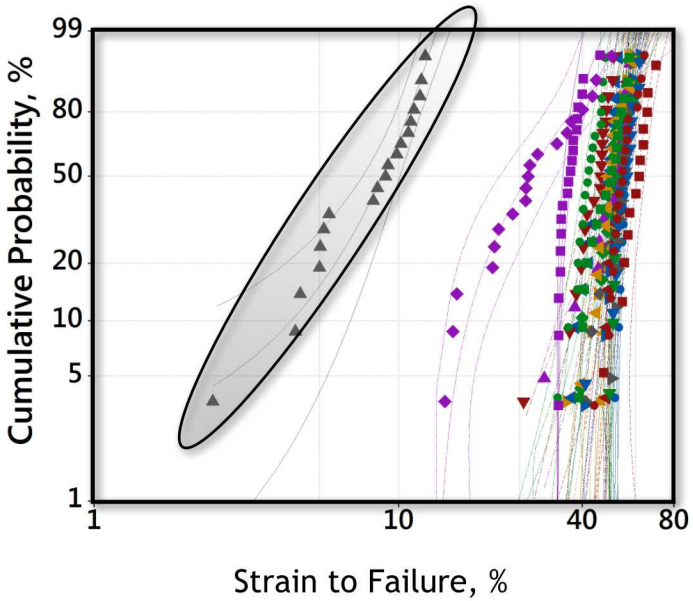




Generation 2 HTT AM Geometry

1 column x 25 rows
25 tensile dog bones per build
1 mm x 1 mm tensile gage section
Internally fabricated by SNL





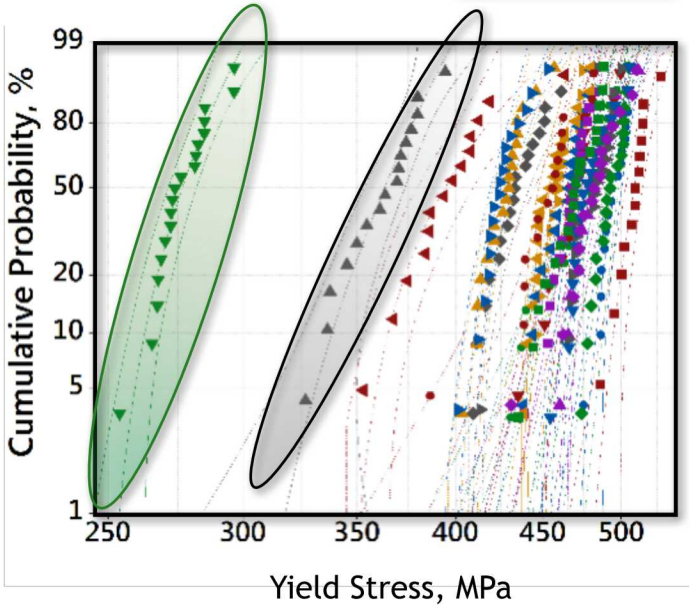


Image Processing

Images must be properly prepared for three-dimensional reconstruction and porosity analysis by:

- Pre-processing to improve image quality, remove extraneous data, and accentuate features of interest.
- Segmentation to create a binary image format. Associates individual pixels with either material or voids.

Pre-Processing

Feature Identification

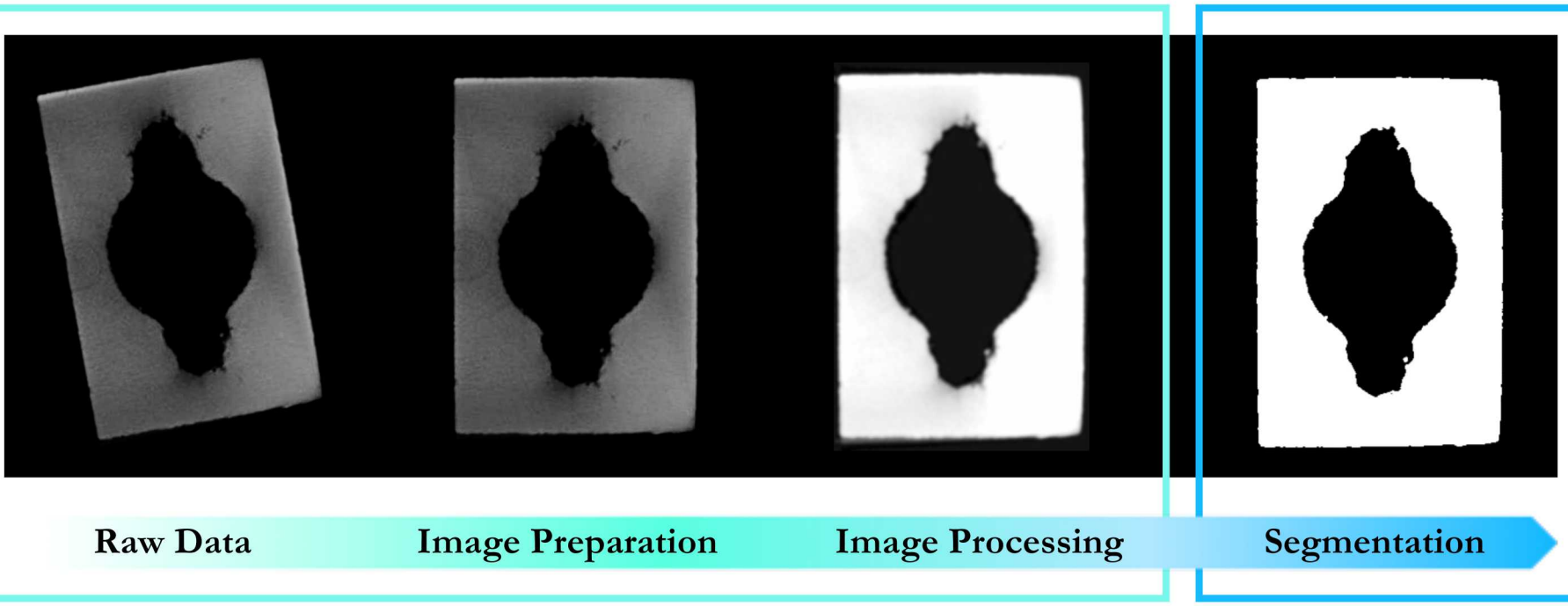


Image Processing Toolbox

Over 20 image processing and three-dimensional analysis scripts created. Each is fully customizable and adaptable for different data sets. These scripts allow automated, batch processing necessary for organization and analysis of big data.

Image preparation (6)

Automated image preparation scripts:

- Rotations
- Cropping
- Image selection and renaming
- Image alignment procedures
- Region of interest definition
- Image noise reduction

File organization:

- Creates uniform file locations.
- Reports meta-data

Matlab Dream3d Fiji/ImageJ

Image Processing (5)

Normalizing image intensity:

- Bimodal histogram analysis. Normalizes image intensity throughout an image stack.

Image smoothing:

- Three dimensional smoothing filters with customizable options.

Advanced filtering:

- Removes uneven background intensity while preserving local image features

Matlab Dream3d

Segmentation (4)

Global threshold:

- Multiple threshold values can be selected and compared.
- Different segmentations can be combined.

Local threshold:

- Adapts to local image criteria. Accepts custom or established threshold methods.
- Full customization of local search areas and paths.
- Allows baseline filtering.

Matlab

3D Reconstruction (8)

Reconstruction:

- Interactive 3D visualizations.
- Create flythrough movies and rendered images.

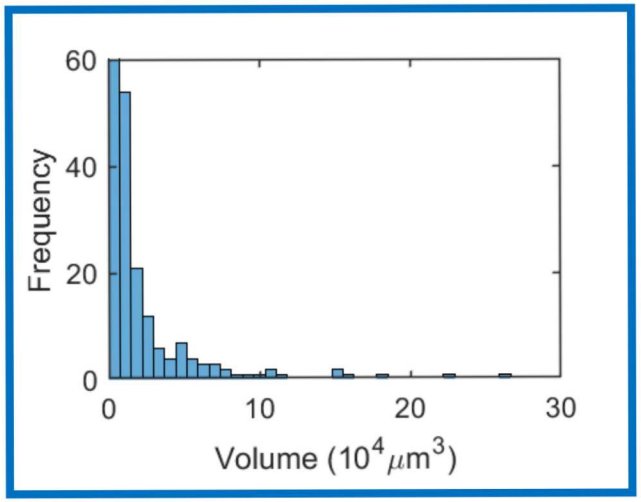
Quantitative analysis:

- Individual features of interest and statistical distributions.
- Selectively analyze certain regions or features.
- Plotting and visualization of statistical measures.

Matlab IDL

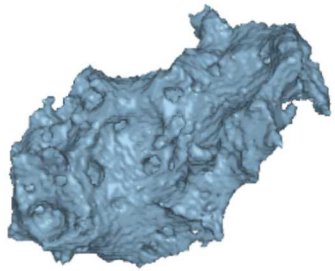
Assessment Metrics – **Scalar**

First order



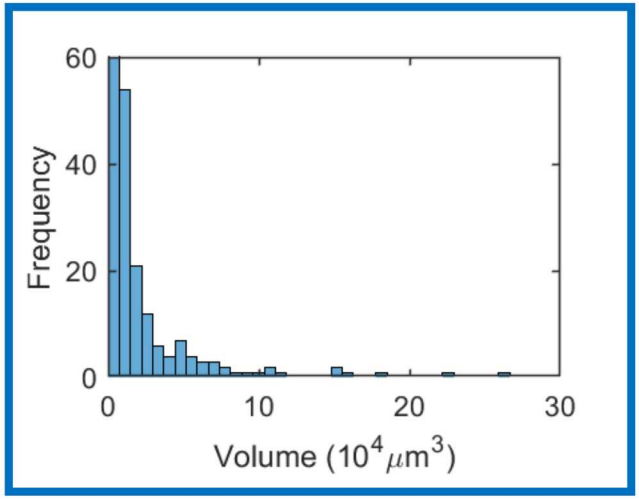
Characterize individual bodies:

- Measure volume by counting voxels
- Calculate equivalent spherical diameters

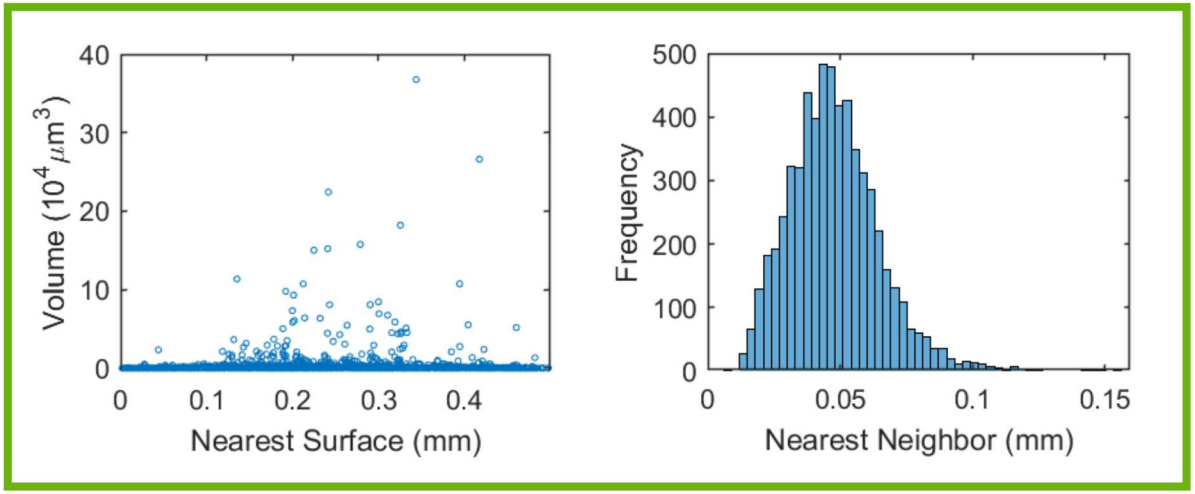


Assessment Metrics – **Relational**

First order

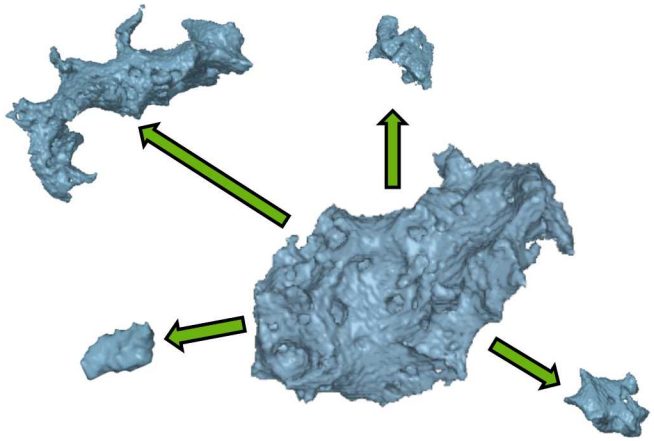


Second order



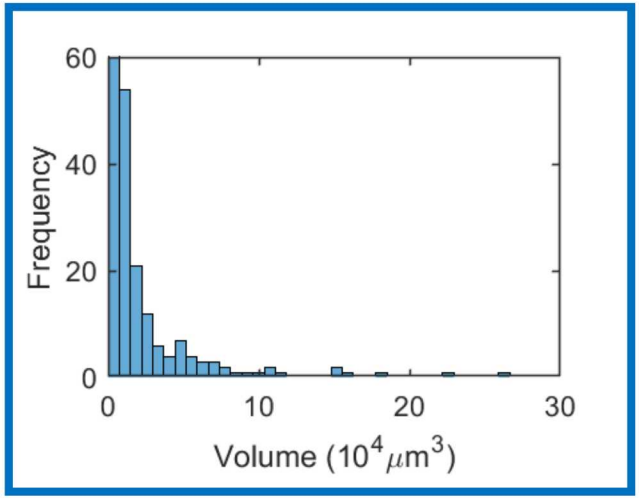
Analyze body networks:

- Determine void locations within the specimen
- Find nearest neighbor distances
- Relate spatial information to other void metrics

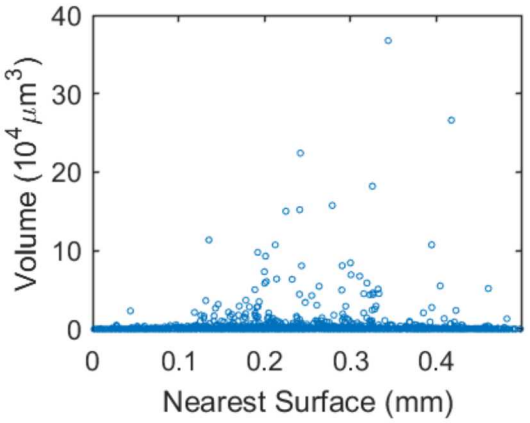


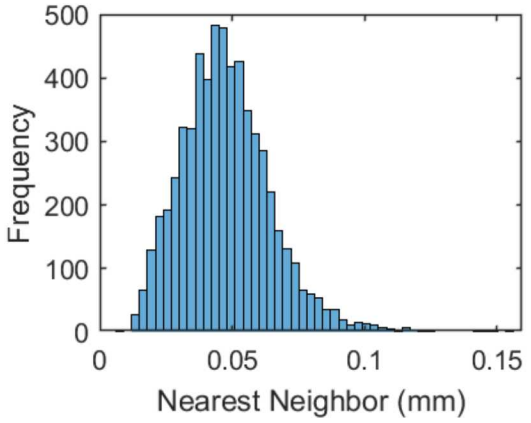
Assessment Metrics – **Contextual**

First order

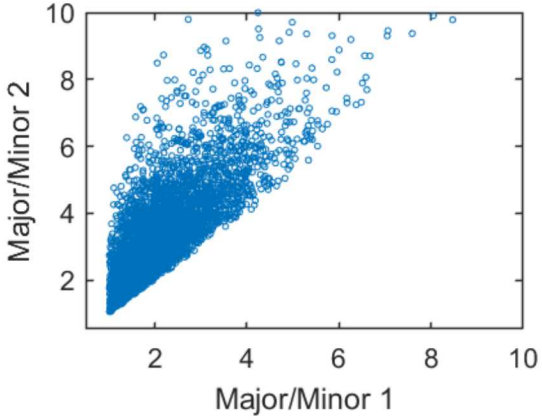


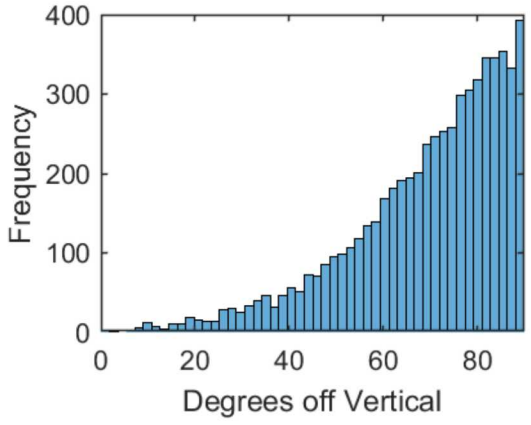
Second order





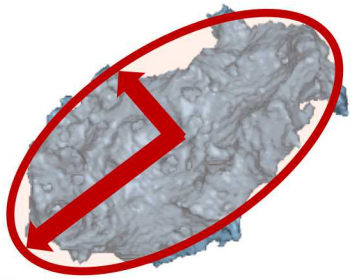
Third order





Characterize body shape, size and morphology:

- Fit shapes to voids. Find aspect ratios and shape parameters
- Measure orientation of voids

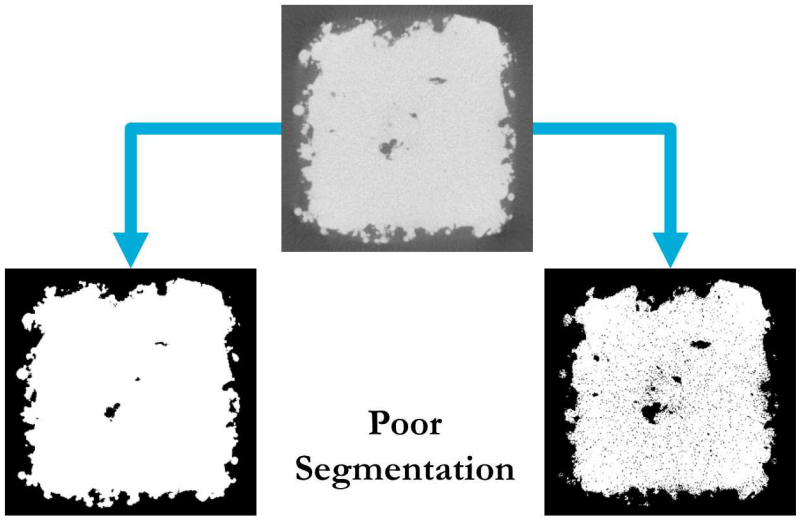


Ellipse fit

Effects of Segmentation

Improper segmentation will adversely affect results, **but by how much?**

Original image

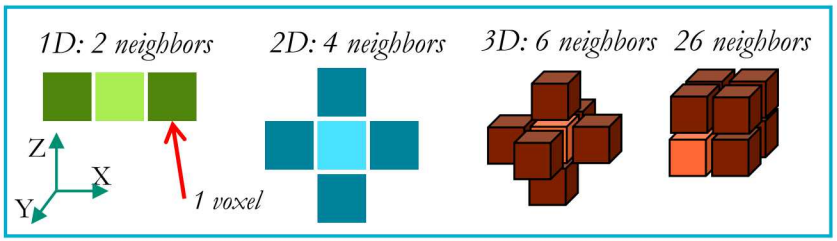


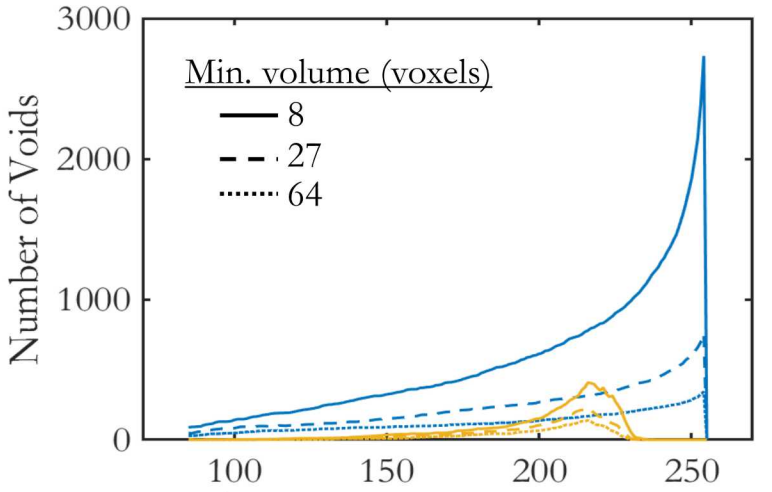
Poor Segmentation

Overly Conservative

Overly Ambitious

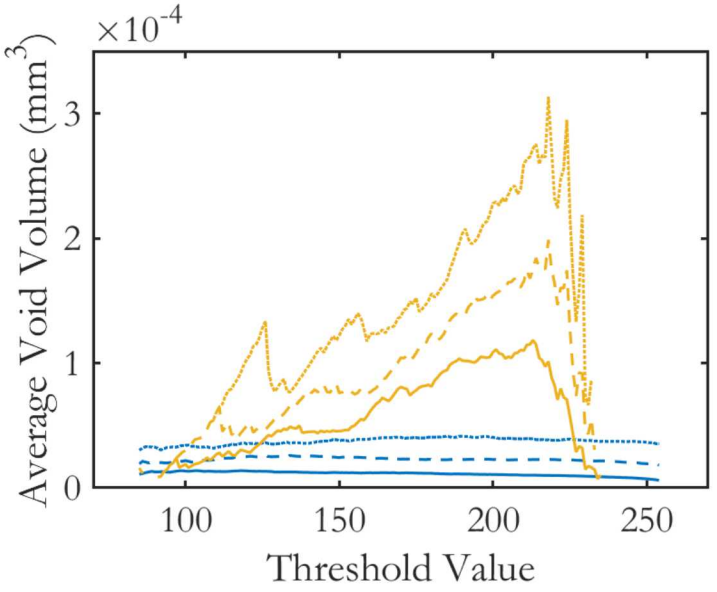
Neighboring Voxel Searching





Mechanical Serial - Sectioning

µCT



µCT

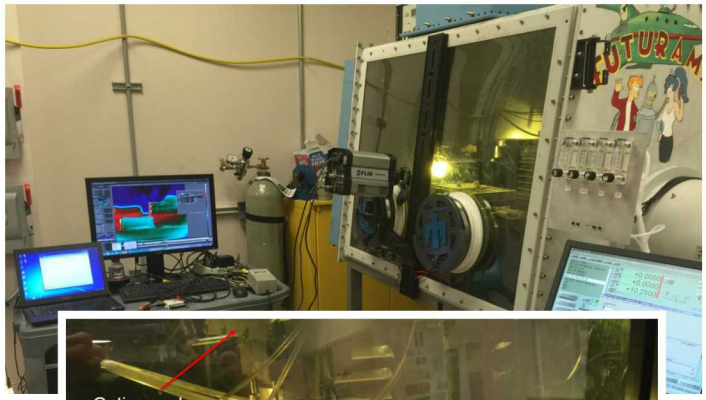
Mechanical Serial - Sectioning

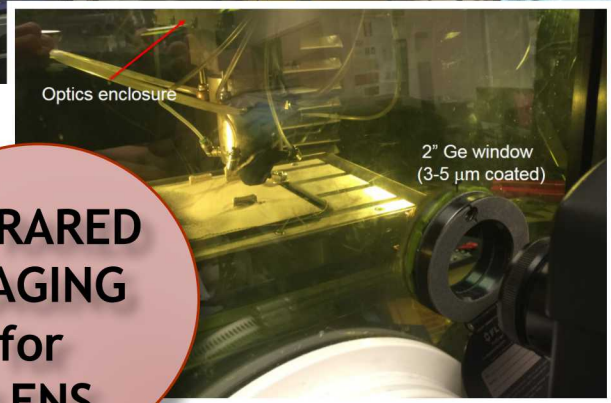
3D analysis is strongly influence by:

- Segmentation decisions
- Image acquisition method and resolution
- Minimum detectable volume (voxels)
- Voxel neighbor scheme

IN-SITU DEFECT DETECTION FOR ADDITIVE

In-Process Thermal Characterization



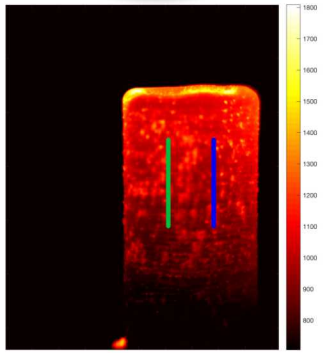


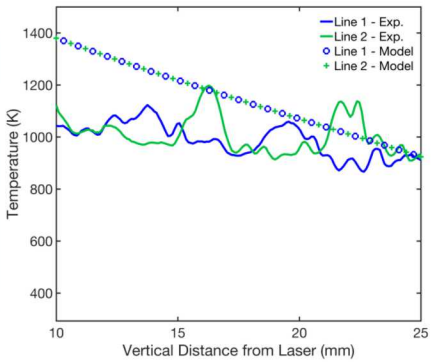
INFRARED IMAGING for LENS

ProX 200

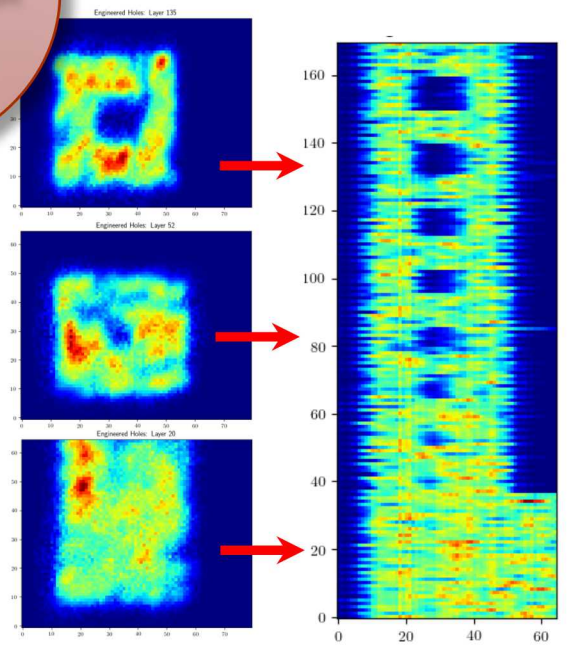
ThermaViz installed in ProX 200

THERMAL IMAGING for POWDER BED





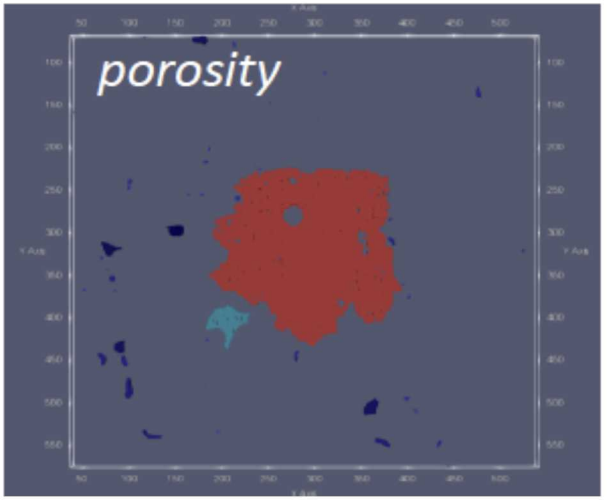
experiment simulation

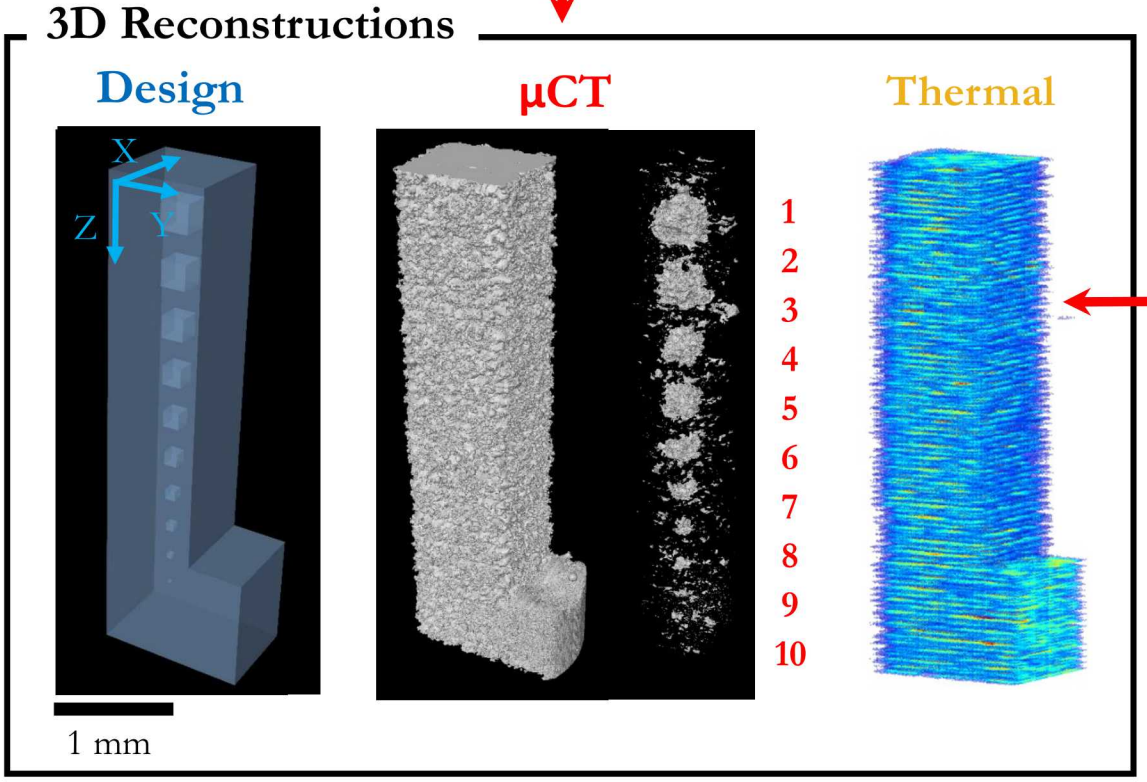


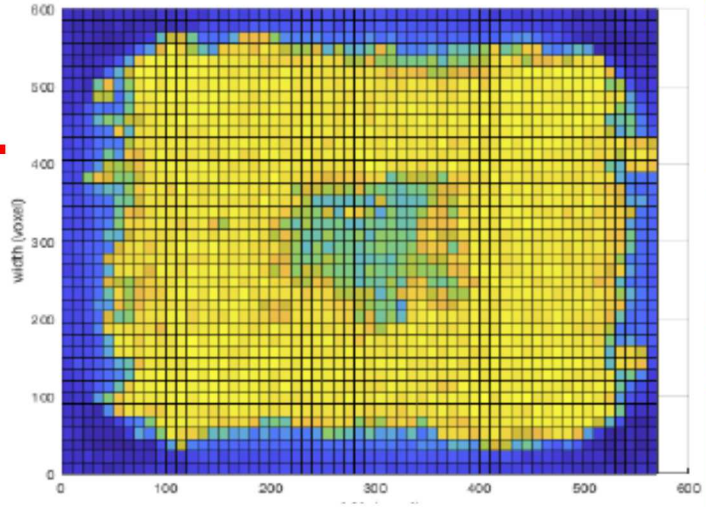
B. Jared, D. Dagel, E. Schwaller, J. Keopke. J. Mitchell, D. Saiz

Multi-Modal Data for Defect Identification

Intentional and unintentional voiding is identifiable via in-situ thermal imaging for powder bed fusion, however variation in resolution between imaging techniques present challenges in one-to-one correspondence with μCT and other post-mortem techniques







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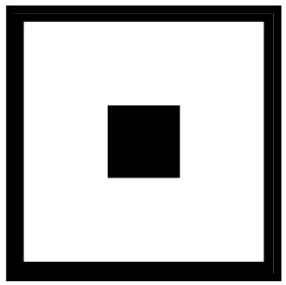
Multi-Modal Data for Defect Characterization

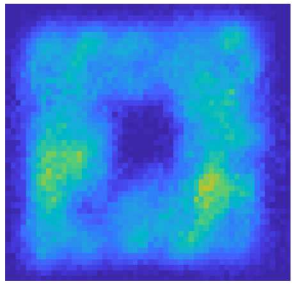
2D Planar Views

Design



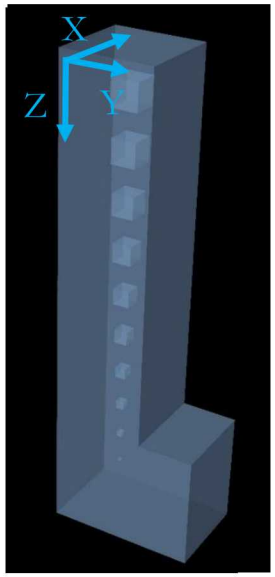
μCT

Thermal

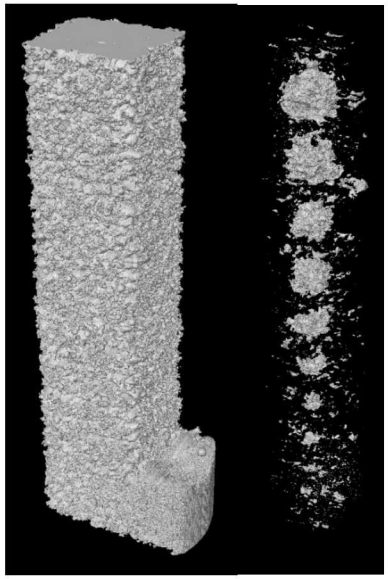


3D Reconstructions

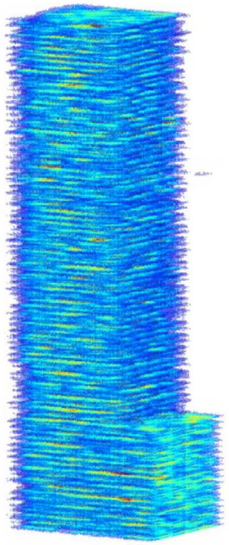
Design



μCT

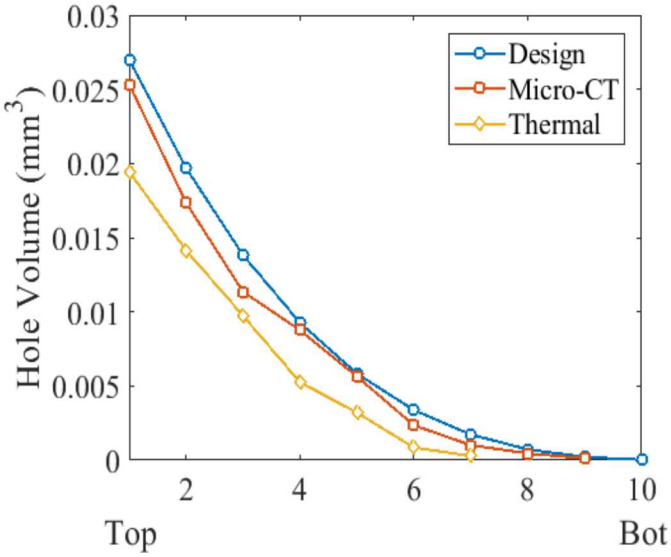


Thermal



1 2 3 4 5 6 7 8 9 10

1 mm



Calculated void volumes from **AM build design**, **μCT characterization** and **thermal imaging** for each intentional defect

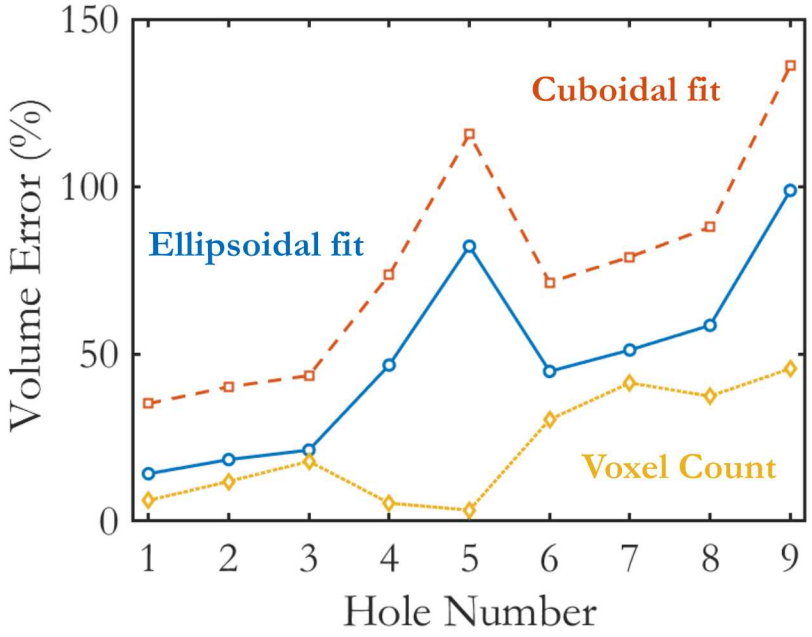
In all cases the designed void volume is larger than the result reported by μCT which is larger than the recorded thermal indicator

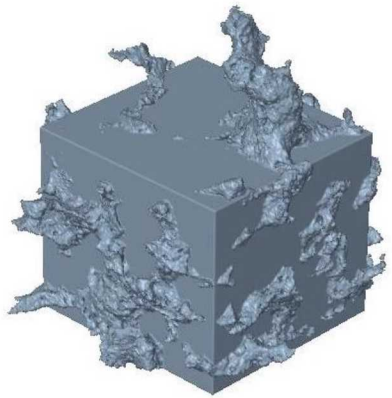
Defect Shape Approximations

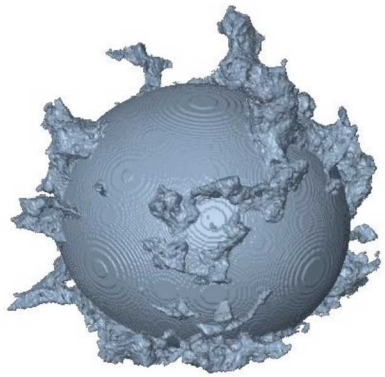
How well do the intentional defects compare to their designed shape?

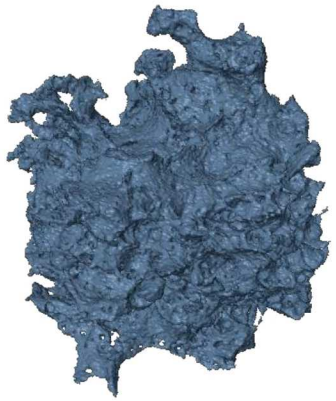
Error estimations are calculated based on differences between the designed void volume and the volume measured by:

1. **Cuboidal fit**
2. **Ellipsoidal fit and**
3. **Direct voxel count from µCT data**





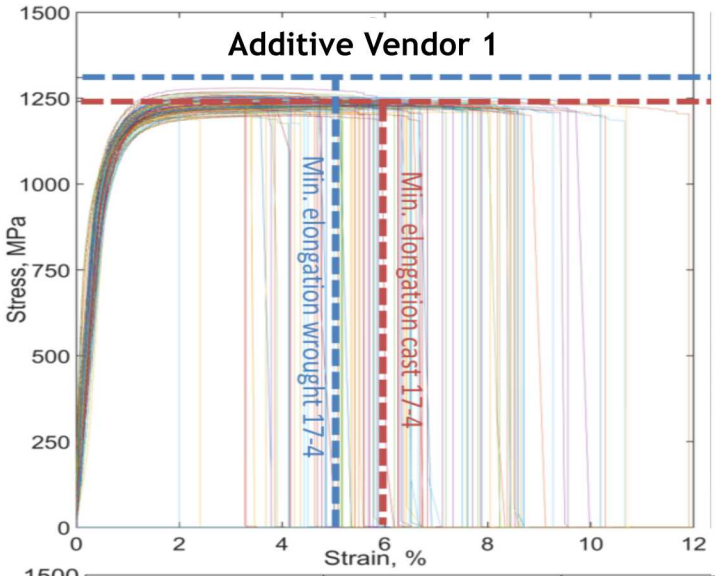


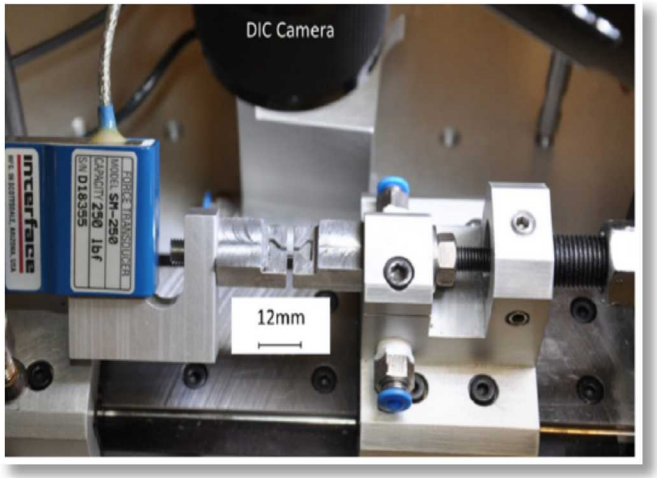


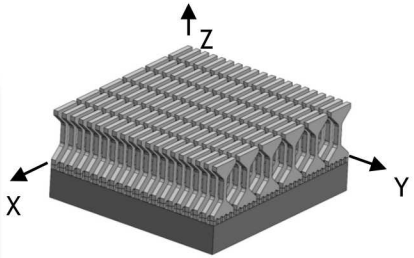
Cuboidal fit **Ellipsoidal fit** **Voxel Count**

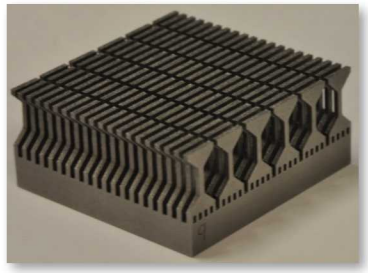
HIGH THROUGHPUT MECHANICAL TESTING IN ADDITIVE BUILDS

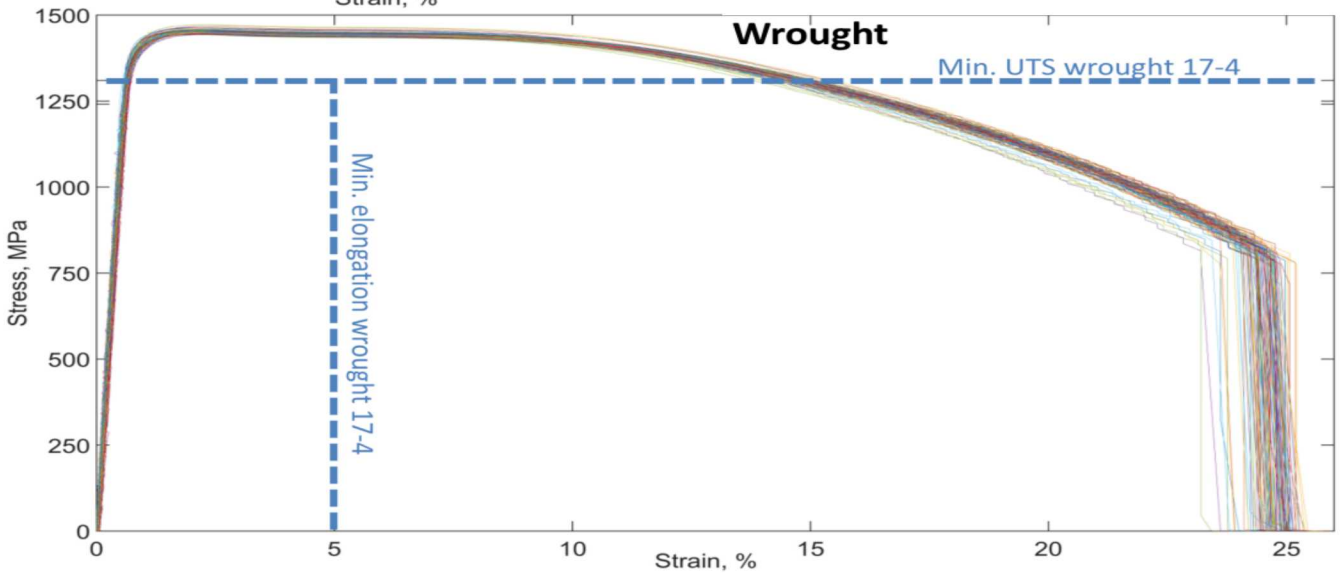
Additive Manufacturing – A Motivating and Challenging Technology











Quantifying mean, outlier & statistical probabilities of performance

Broad variability in strain to failure for AM vs. conventionally wrought

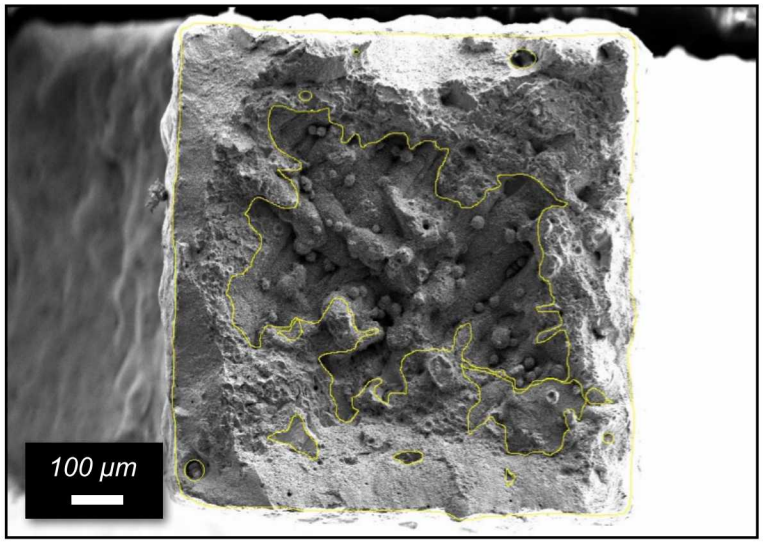
How do we leverage our understanding of performance to inform our predictions?

AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

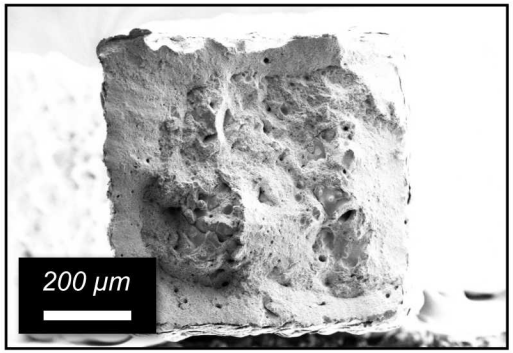
*Salzbrenner, et al., **J. Mat. Proc. & Tech.** vol. 241 (2017) pp. 1-12*

B. Boyce, B. Salzbrenner

Fractography – 17-4 PH Stainless Steel

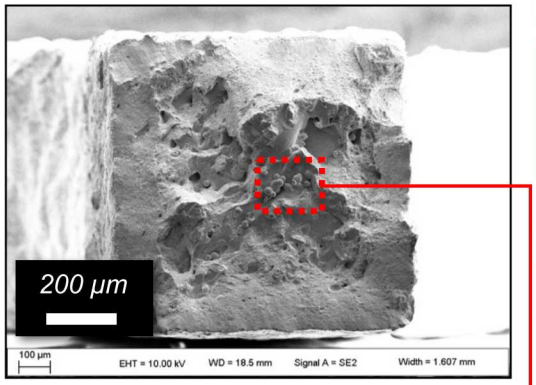


Strain-to-Failure: 10.1%

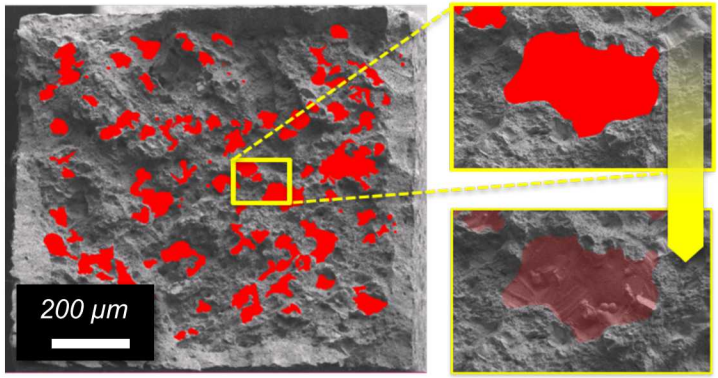


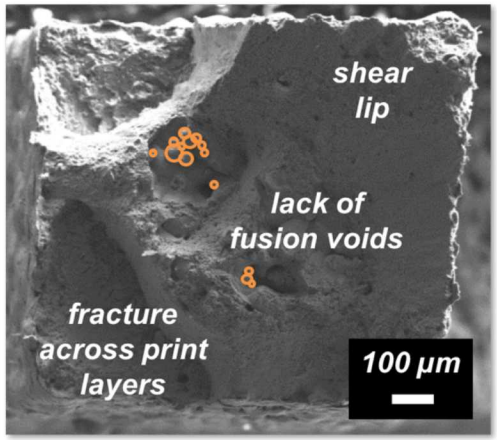
- ~6 area% of fracture surface contains lack-of-fusion defects
- Partial shear lip formation

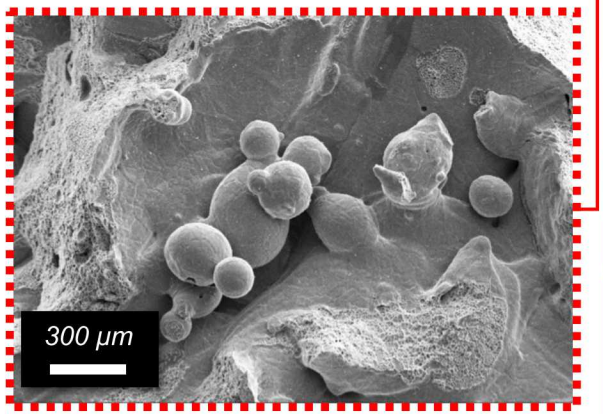
Strain-to-Failure: 1.8%



- ~22 area% of fracture surface contains lack-of-fusion defects
- Gross defects primarily all internal
- No shear lip formation—macroscopically brittle failure

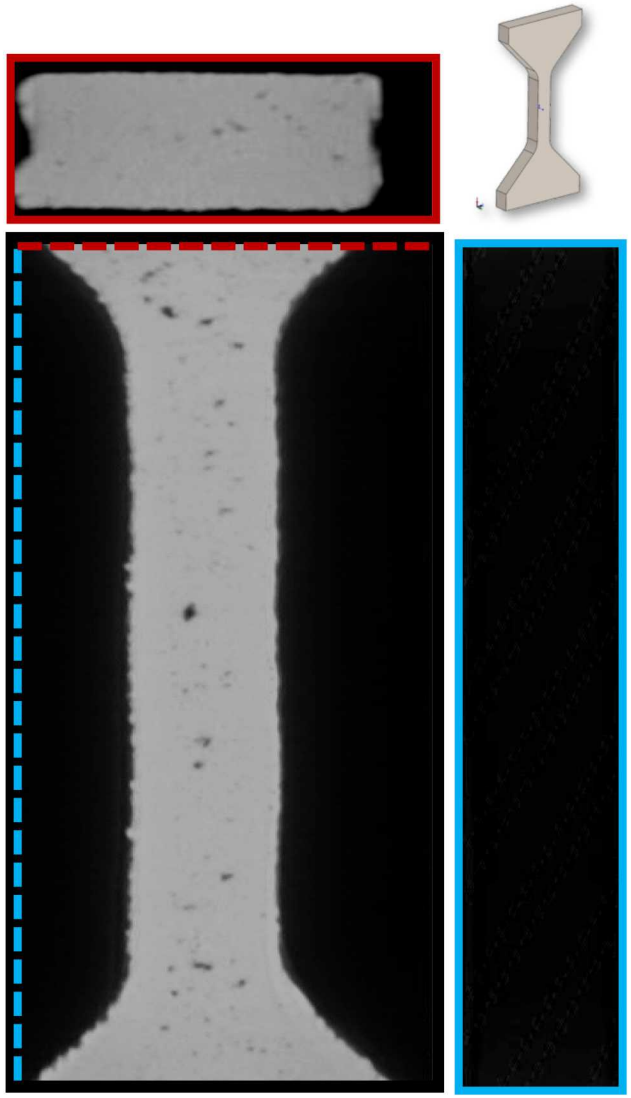






Boyce, et al., ***Adv. Engr. Mat.*** *vol. 19 (2017) pp. 1-10*

μ-Computed Tomography



North Star Imaging,
X50 XViewCT Cabinet System
YXLON Demountable Microfocus Tube
(10-225kV)

Nikon Avonix M2 225/450 kV
Helical Scanner

Gen 1 μCT approach

7-10 μm per voxel edge
defect threshold > 20μm ESD
~ 60 MB per dogbone (image stack)
7+ GB for μcT of entire build group
operating at 220kV
Varian 2520V flat panel detector

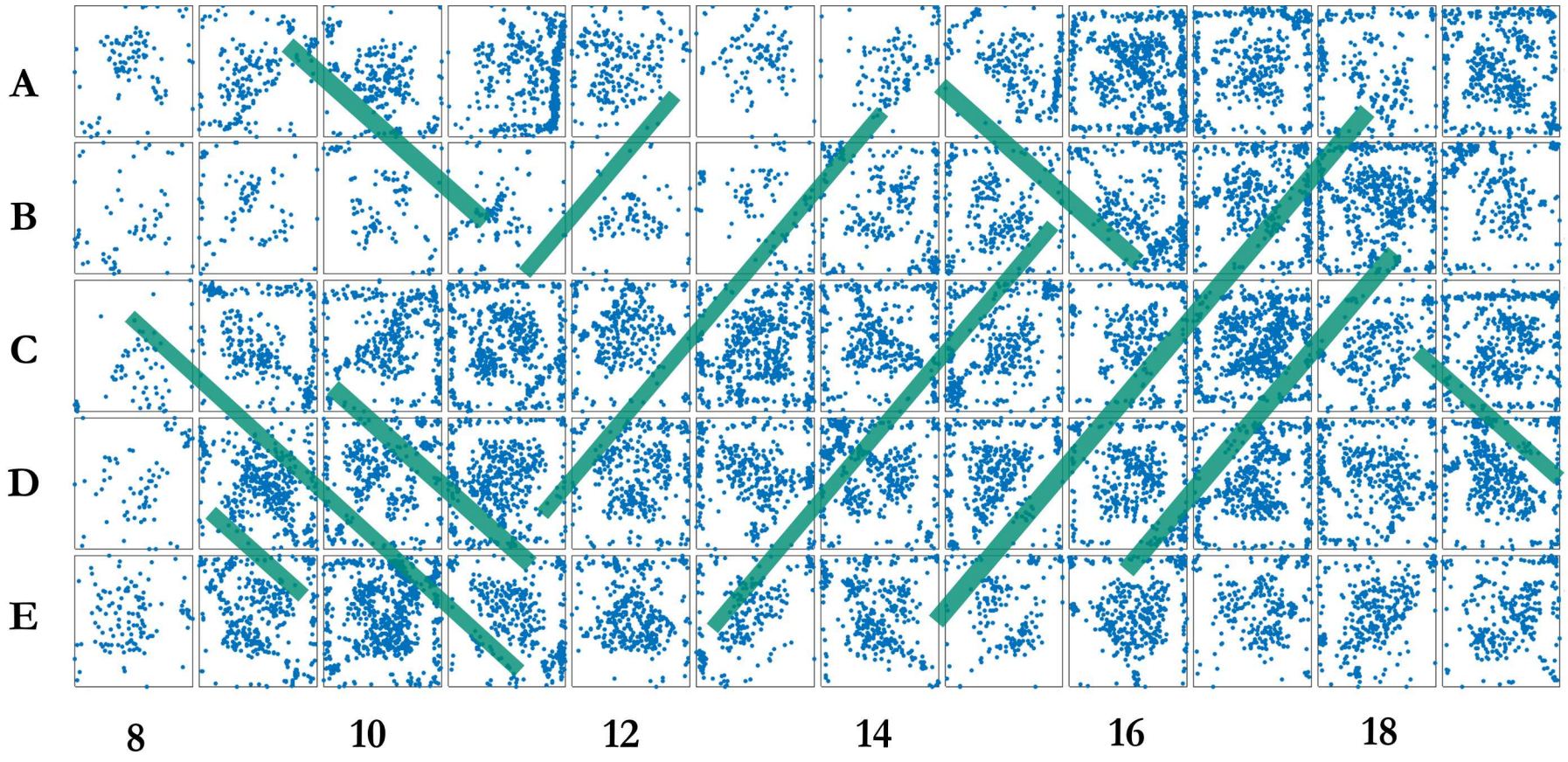
Gen 2 μCT approach

14.9 μm per voxel edge
defect threshold > 26μm ESD
~ 70 MB per dogbone (image stack)
1.75 GB for μcT of entire build group
operating at 350kV
Perkin Elmer 1611, 100μm detector

Global Void Projections

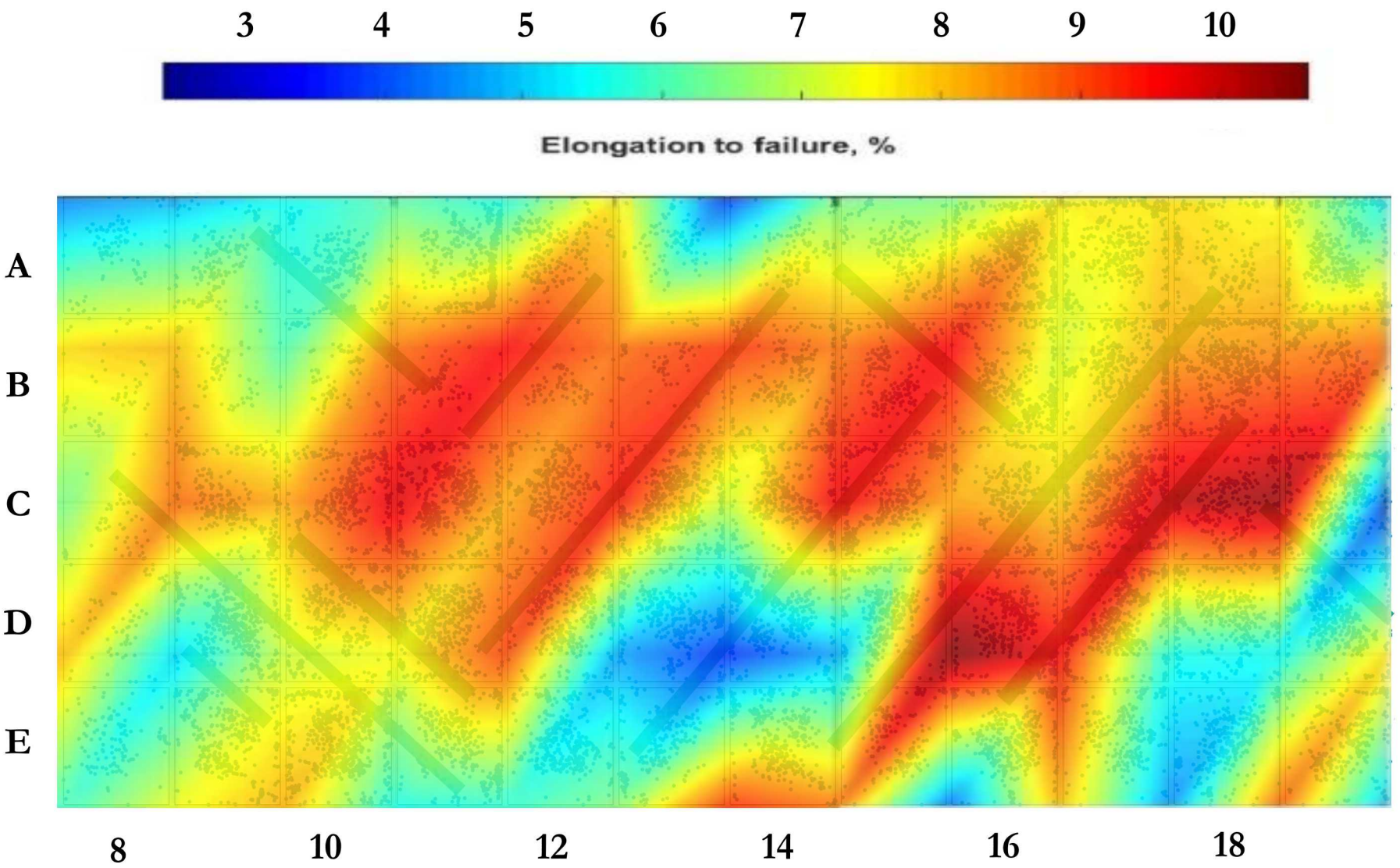
XY-projections of voids throughout build (top-down view through each gauge region)

Each square represents a single specimen within its as-built location. Green lines highlight long range order of void absence across specimens throughout the build



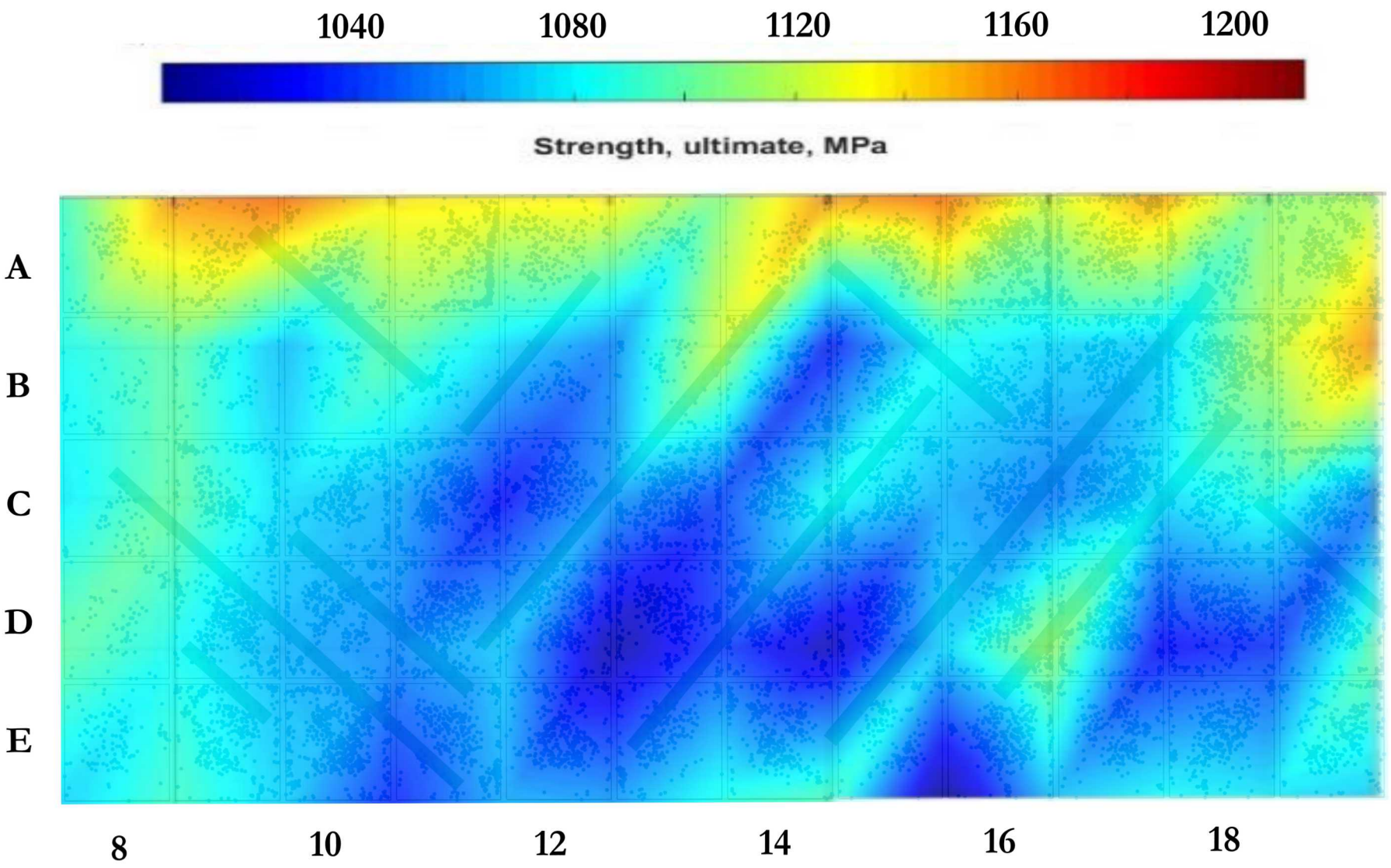
Global Mechanical Performance

Percent Elongation to Failure (%)

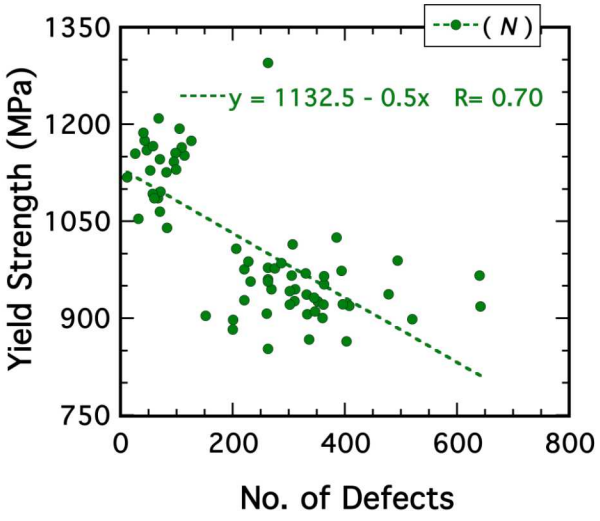


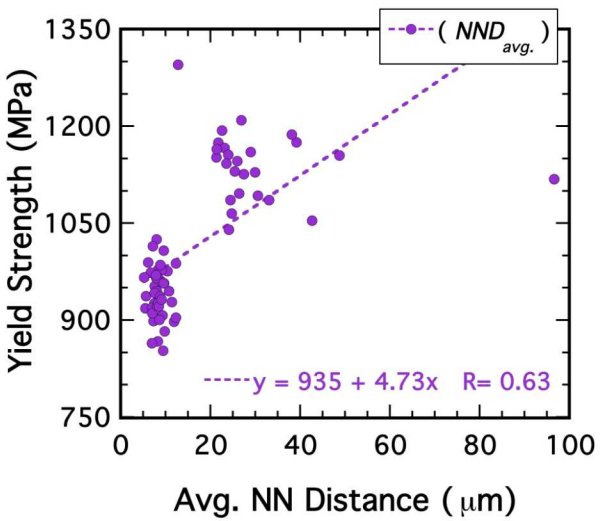
Global Mechanical Performance

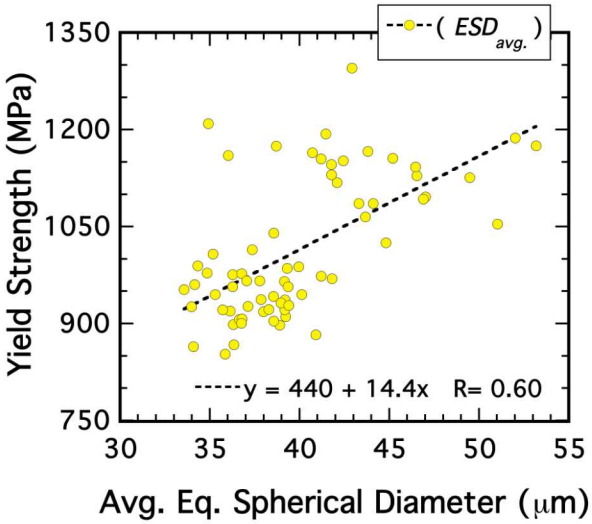
Ultimate Tensile Strength (MPa)

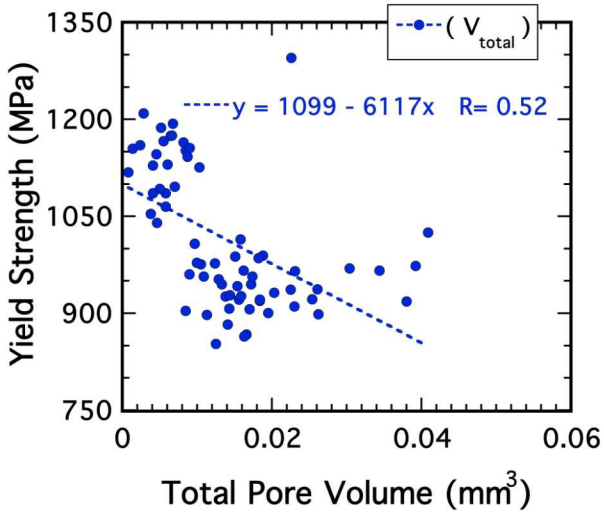


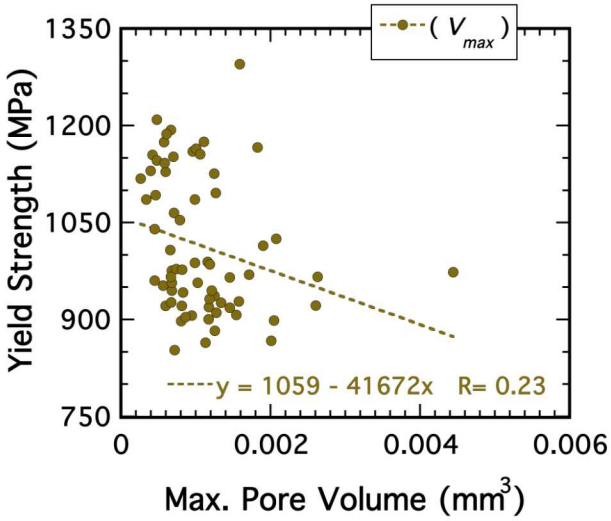
Global Correlations with Yield Strength











In relation to Y.S.

Measure	R value	R^2
No. of Defects	-0.71	0.50
Avg. NN Distance (mm)	0.70	0.40
Avg. ESD (mm)	0.60	0.36
Max CSA Redux (mm^2)	-0.58	0.38
Total Pore Volume (mm^3)	-0.52	0.27
Avg. Defect Vol. ($mm^{3)}$	0.50	0.25
Max CSA Redux (%)	-0.49	0.24
Maximum Pore Size	-0.26	0.07

Multivariate Regression

In relation to Y.S.

No. of Descriptors	R^2	No. of Defects (N)	Avg. Defect Volume ($V_{avg.}$)	Avg. Equivalent Spherical Diameter ($ESD_{avg.}$)	Total Pore Volume (V_{tot})	Maximum Pore Volume (V_{max})	Average Nearest Neighbor Distance ($NND_{avg.}$)	Maximum Cross-Sectional Area Reduction (CSA_{redux})
1	.497	X						
1	.398						X	
2	.548	X		X				
2	.542	X	X					
3	.579	X	X					X
3	.579	X		X				X
4	.594	X	X					X
4	.594	X			X		X	X
5	.604	X	X		X		X	X
5	.603	X		X	X		X	X
6	.604	X	X	X	X		X	X
6	.604	X		X	X	X	X	X
7	.604	X	X	X	X	X	X	X

$\sigma_{ys} = 1132 - 0.5(N)$ $R^2 \sim 0.5$

$\sigma_{ys} = 835 - 0.382\ (N) + 6.74\ (ESD_{avg.})$ $R^2 \sim 0.55$

$\sigma_{ys} = 963 - 0.431\ (N) + 5.33\ (ESD_{avg.}) + 3132\ (V_{tot}) - 0.005\ (CSA_{redux})$ $R^2 \sim 0.6$

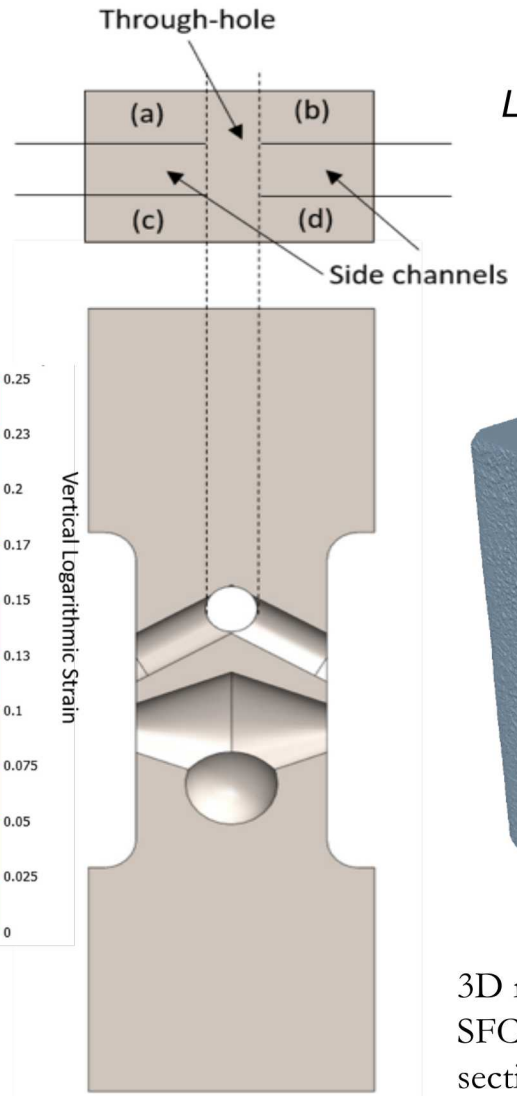
SANDIA'S 3RD FRACTURE CHALLENGE ON ADDITIVE METAL

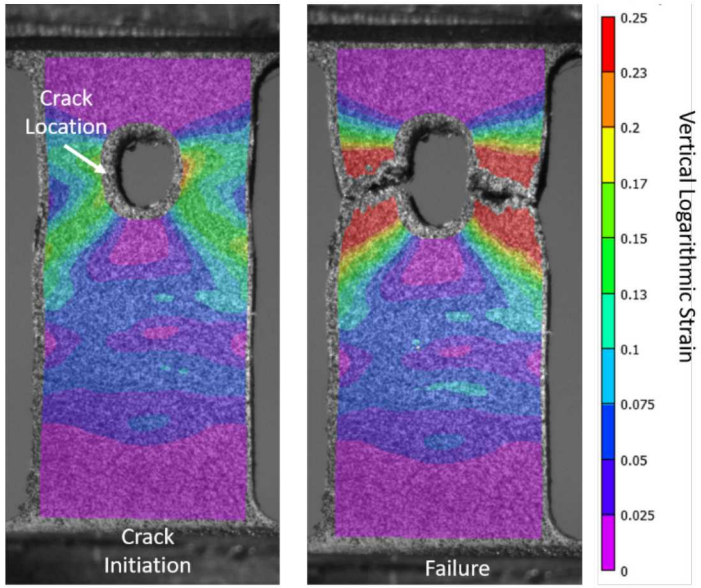
Sandia Fracture Challenge

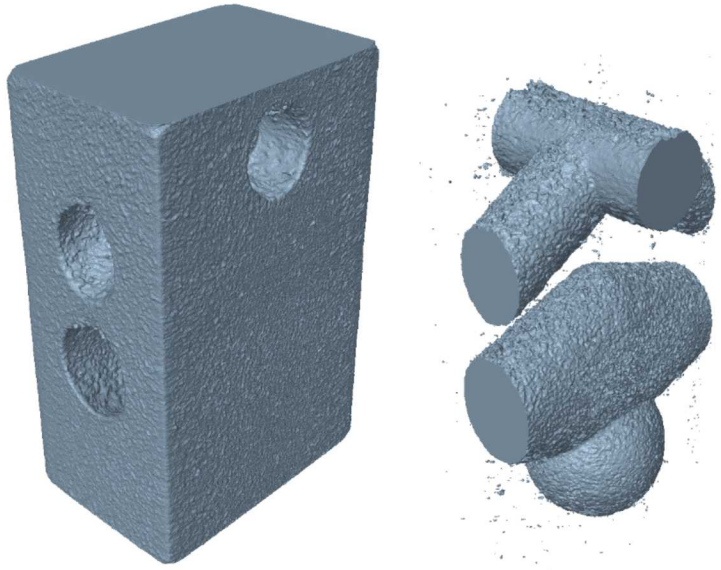
The 3rd Sandia Fracture Challenge: Predictions of ductile fracture in additively manufactured metal

Lead Author: Sharlotte L.B. Kramer

Can we correlate intentional void metrics with mechanical test data in additively manufactured metal?

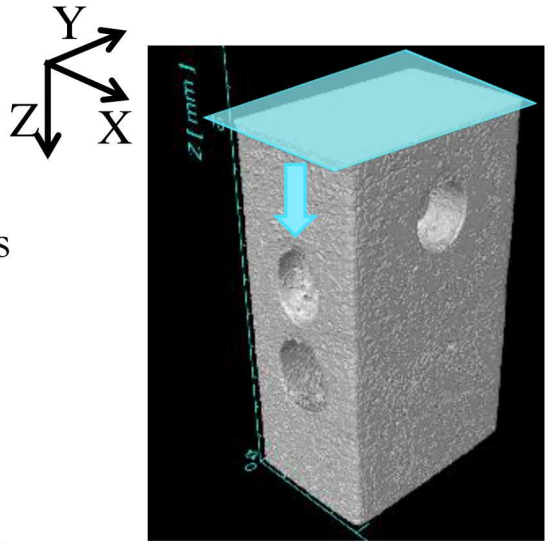






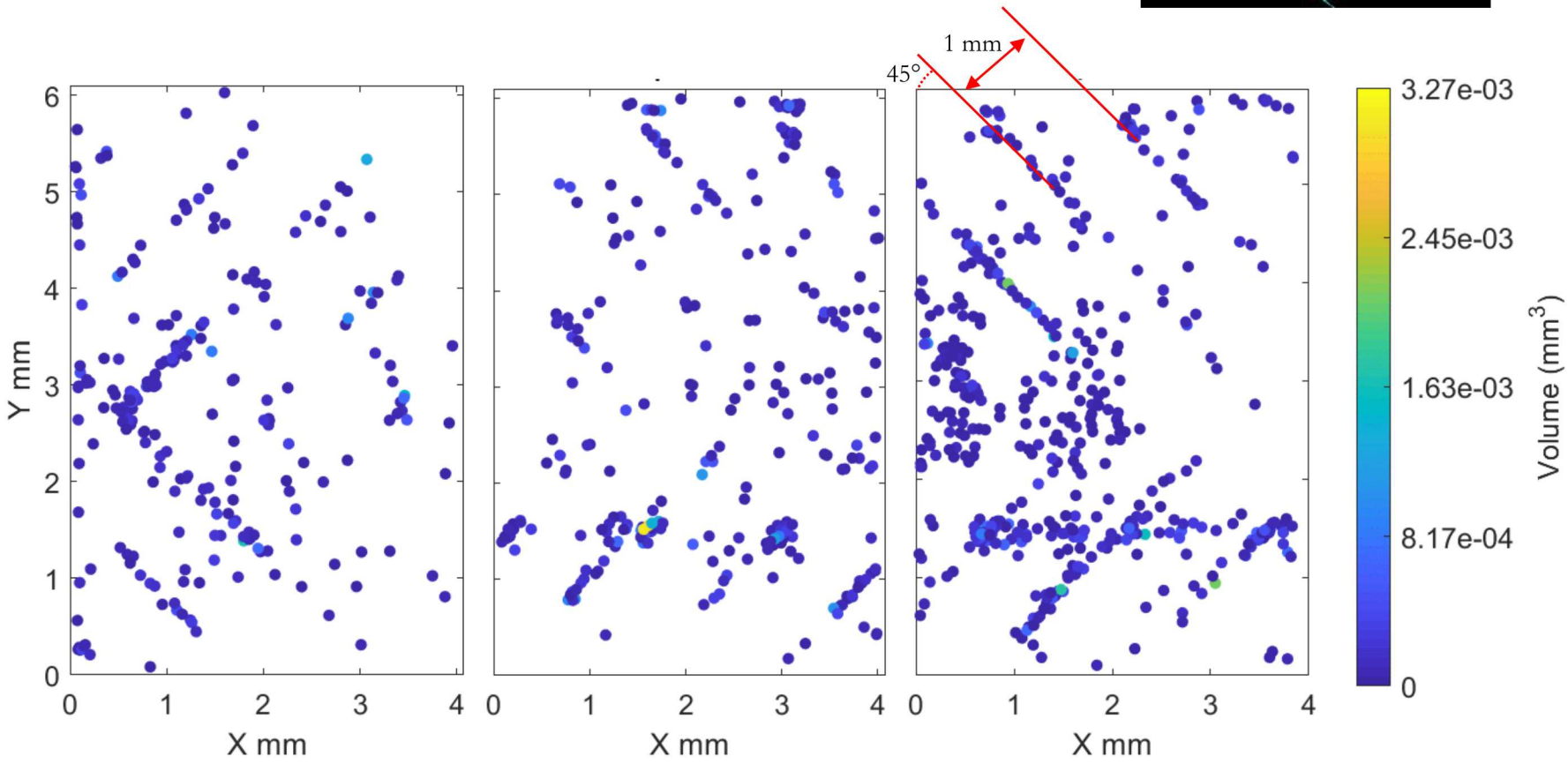
3D reconstruction of the gauge region of a SFC3 tensile dogbone. The solid material gauge section is shown at left and the internal channels and porosity are shown at right).

Sandia Fracture Challenge



Diagonal hatch pattern strongly visible in XY-projections

- 45° orientation of defects with respect to sample surface
- 90° orientation of defect trails to one another
- Approximately 1 mm spacing between parallel defect trails

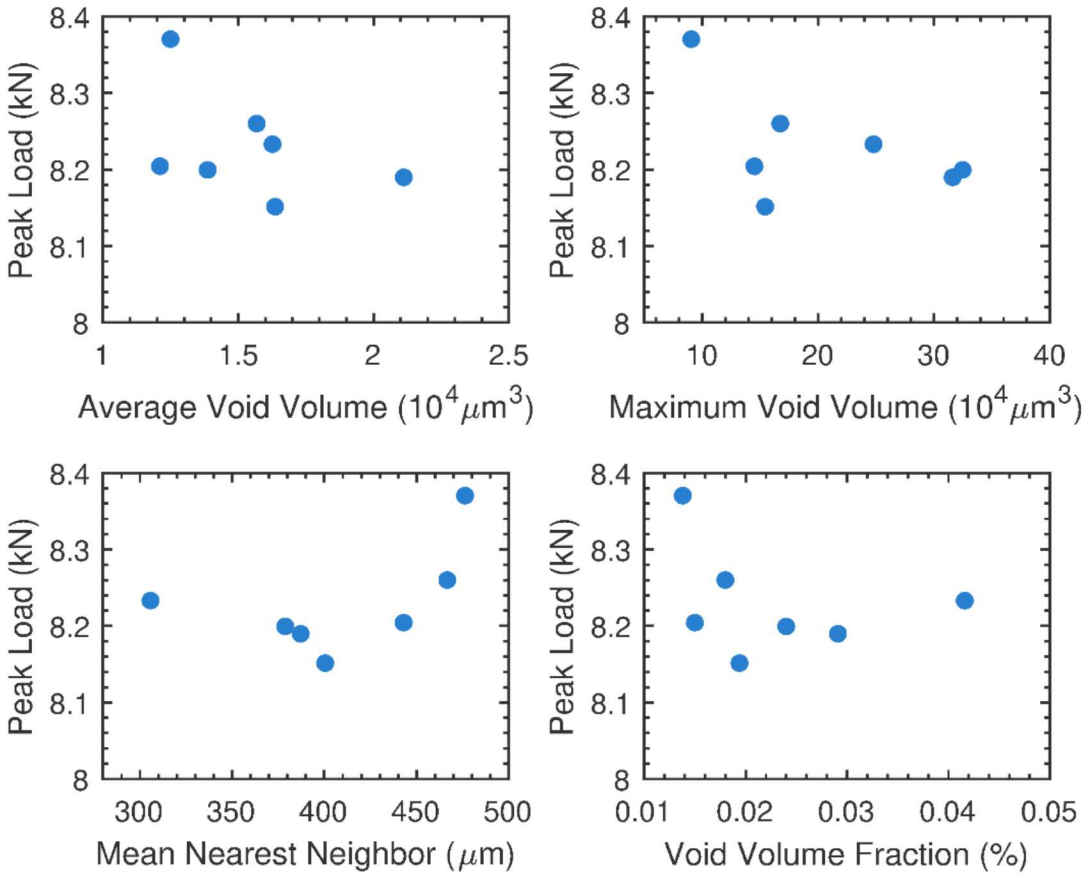


Sandia Fracture Challenge

3D characterizations were reconstructed for seven SFC3 tensile dogbones imaged using X-ray microcomputed tomography

Global void metrics throughout the gauge region of each specimen were examined in relation to mechanical performance in uniaxial tension.

No correlation were observed to exist between global void metrics and overall mechanical performance.

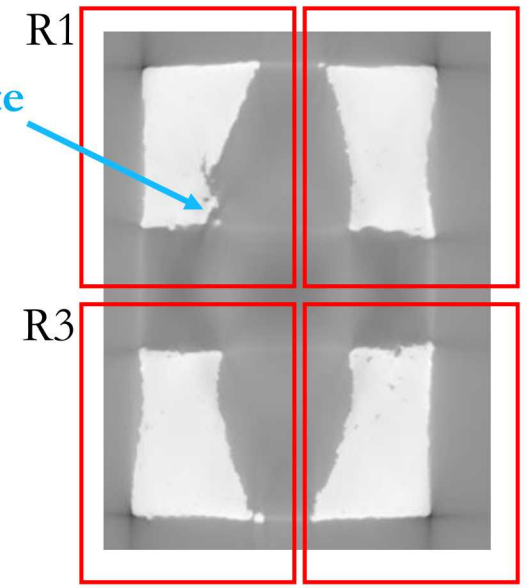


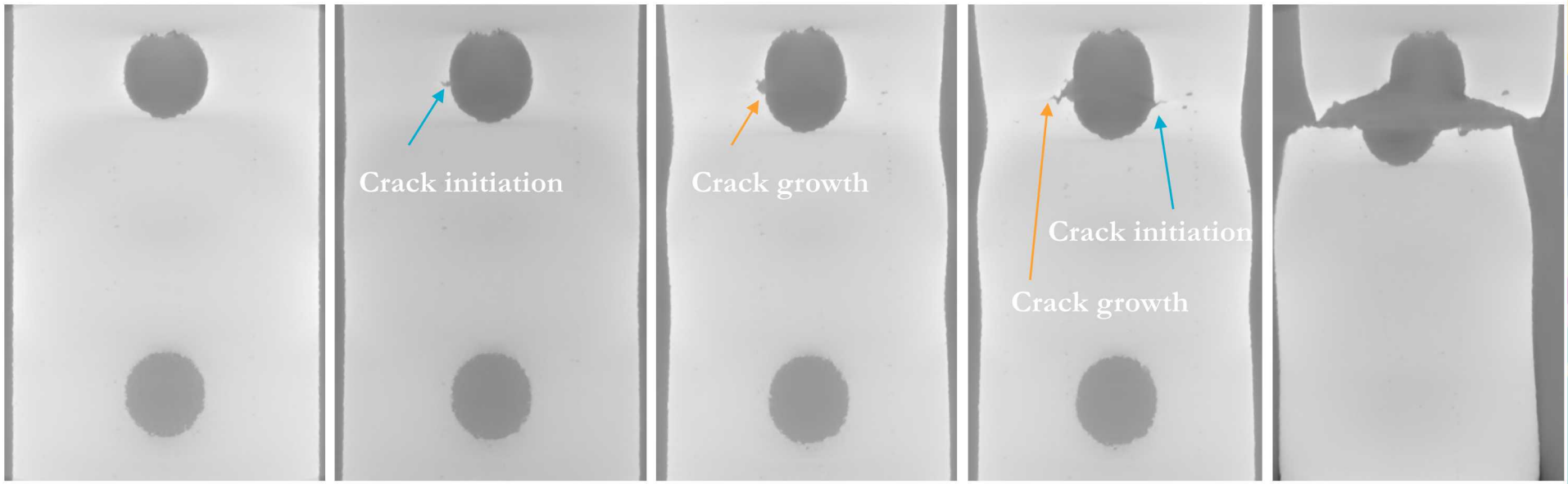
Sandia Fracture Challenge

Cross-section of one SFC3 specimen showing crack initiation and propagation are currently being examined

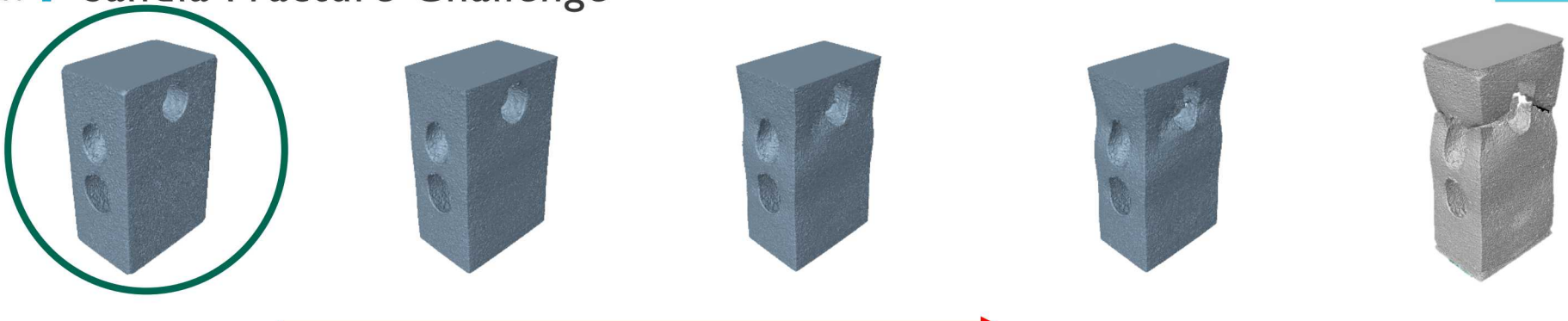
Focus of interrupted tensile test is to map in 3D cracks initiation and propagation.

Each sample provides a 4 locations for crack initiation

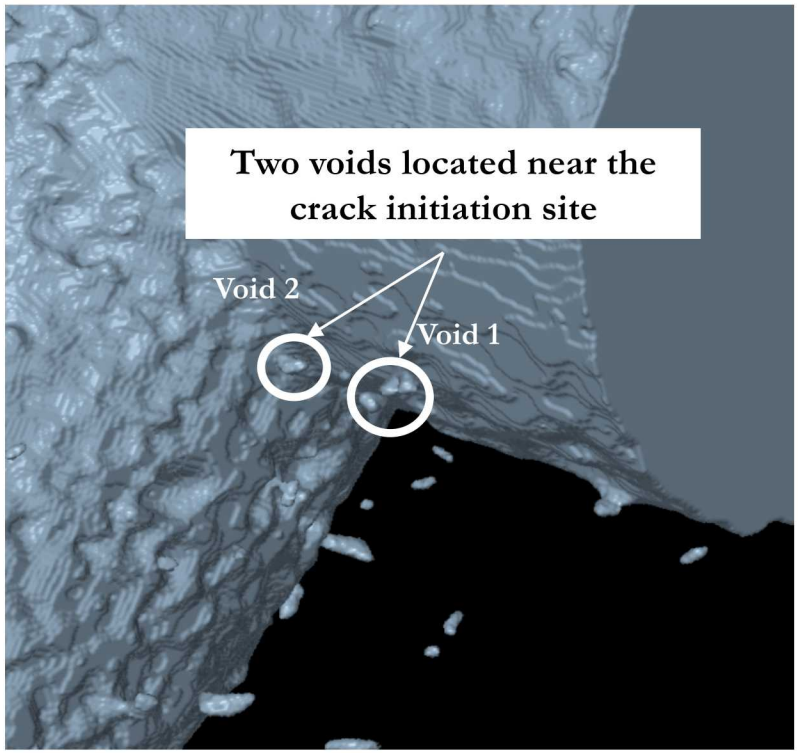




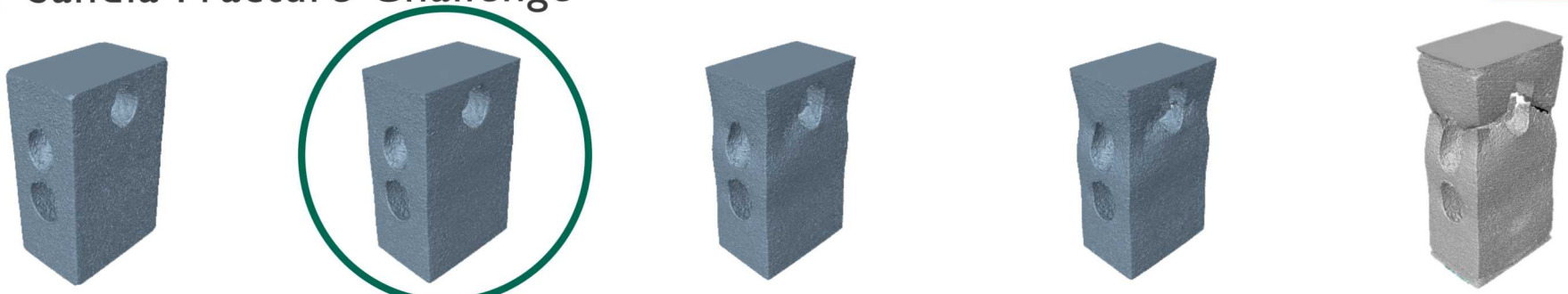
Sandia Fracture Challenge



Pre-test Increasing strain Failure



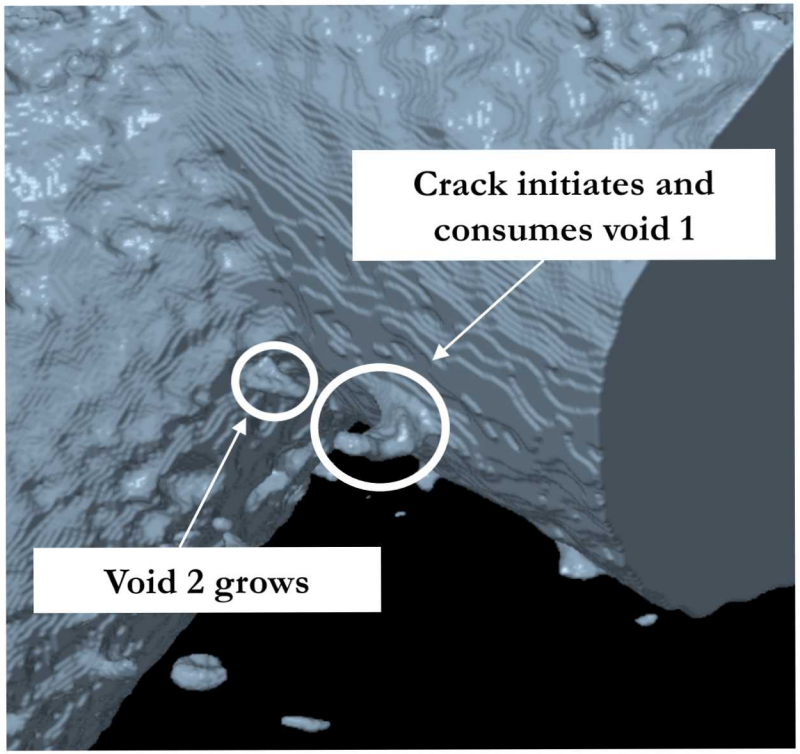
Sandia Fracture Challenge



Pre-test

Increasing strain

Failure

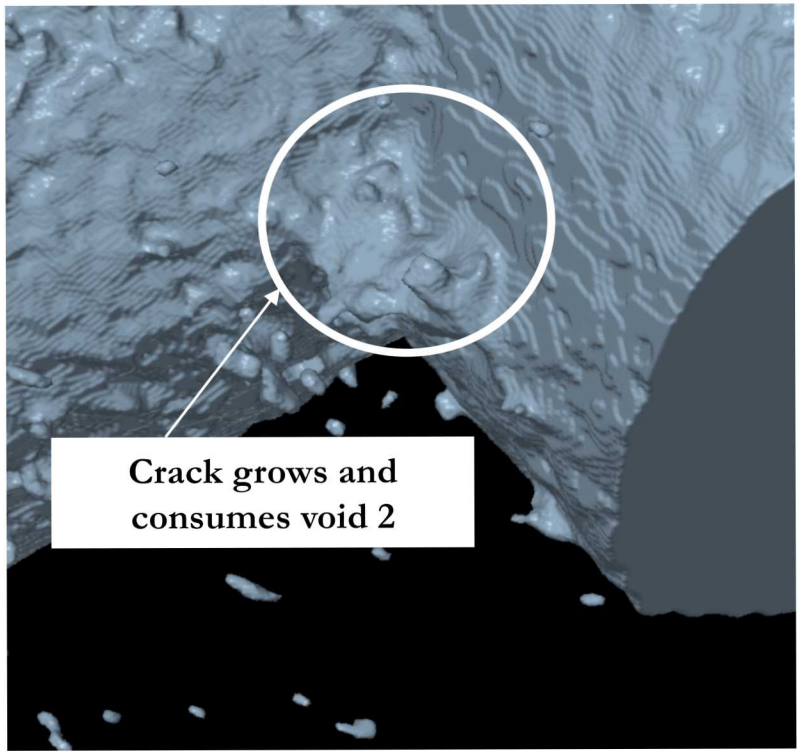


Sandia Fracture Challenge

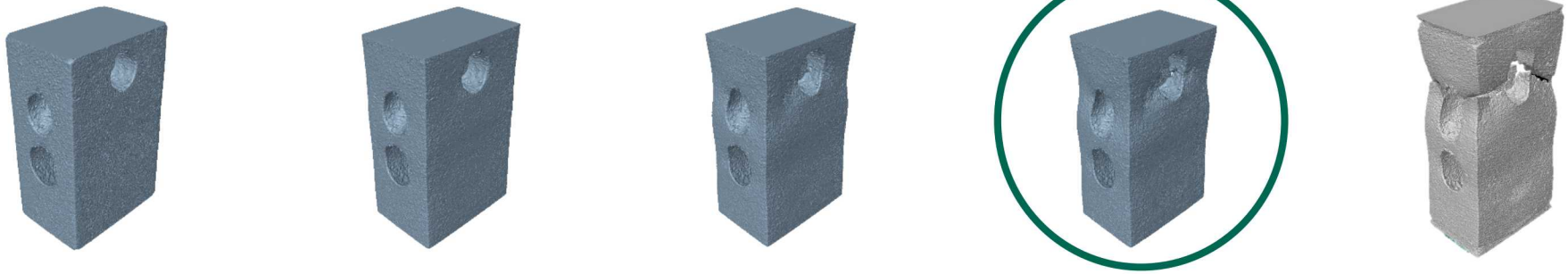
Pre-test

Increasing strain

Failure



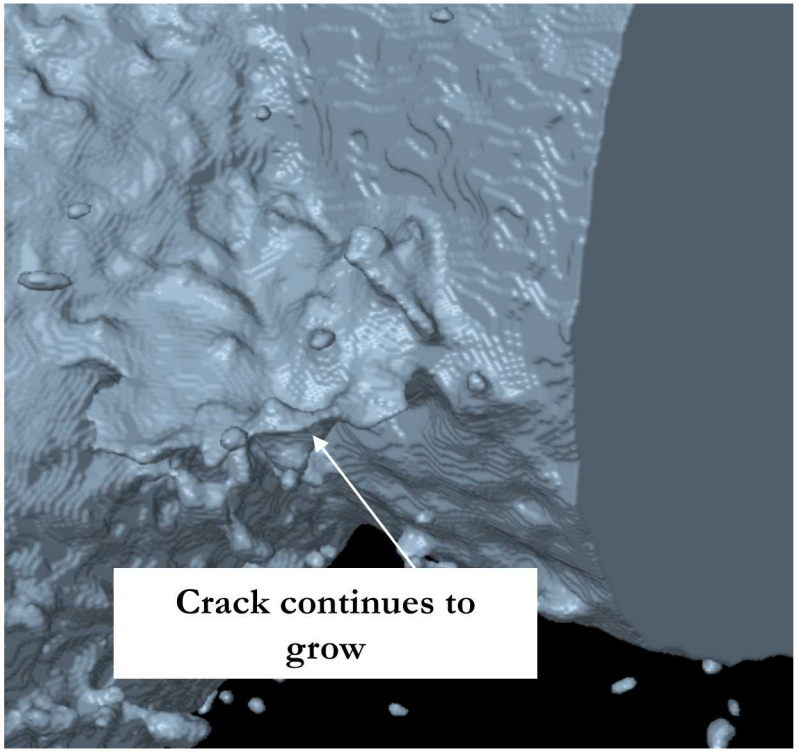
Sandia Fracture Challenge



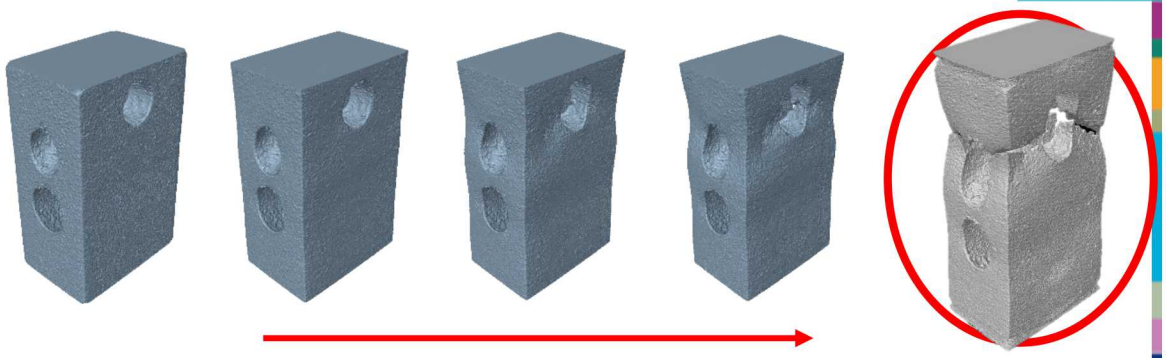
Pre-test

Increasing strain

Failure



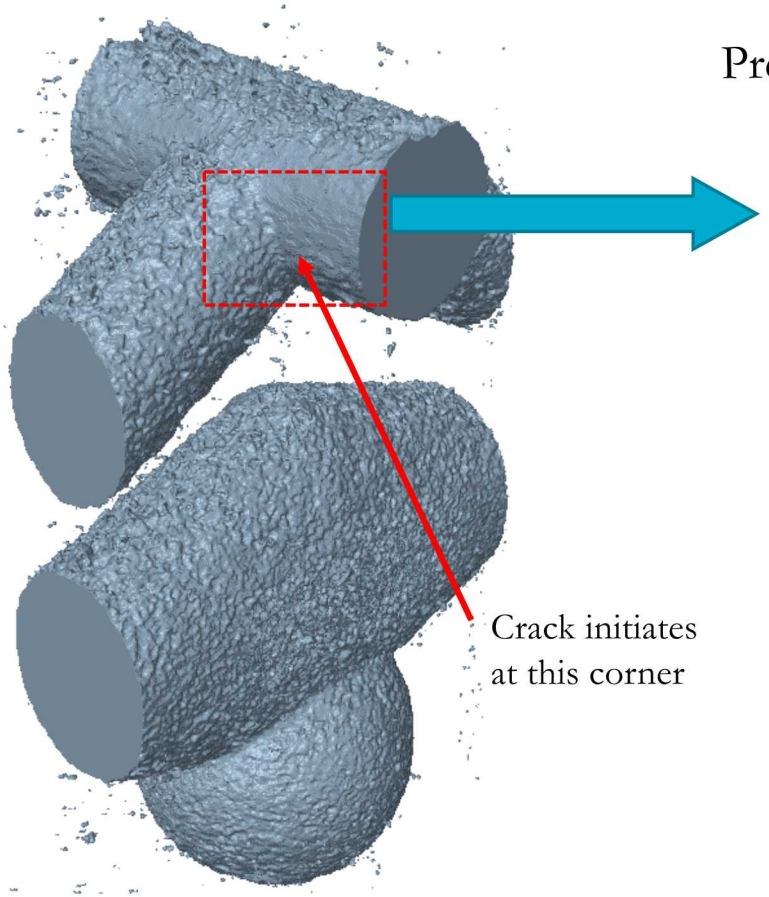
Sandia Fracture Challenge

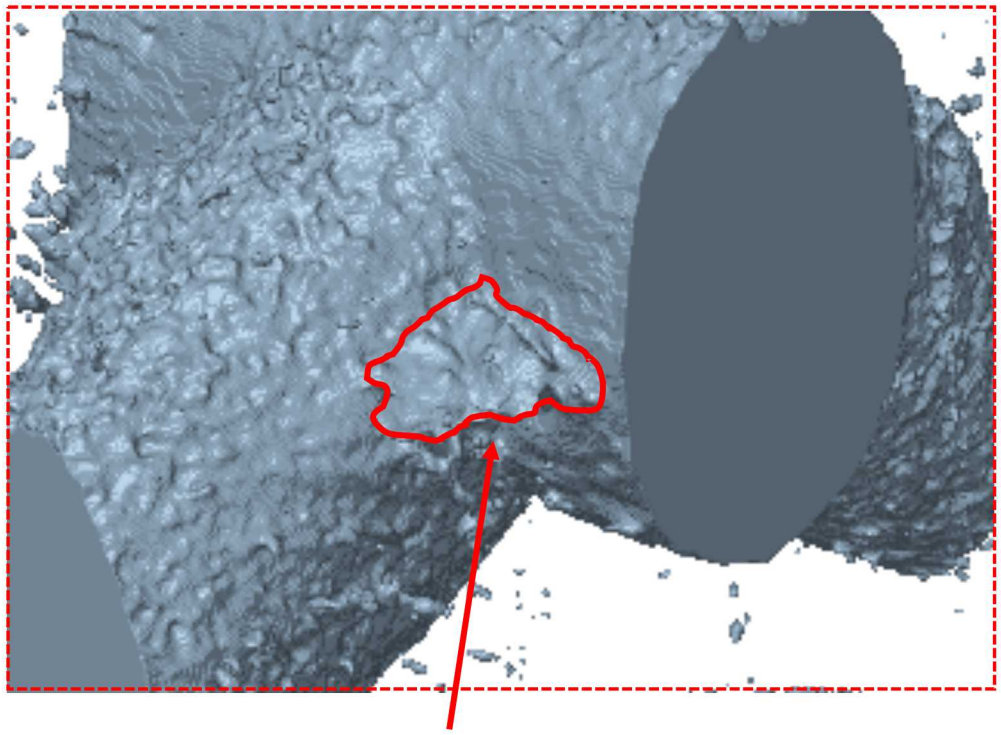


Pre-test

Pre-test Increasing strain Failure

Pre-test





Expanded Crack volume at last step before failure

Summary

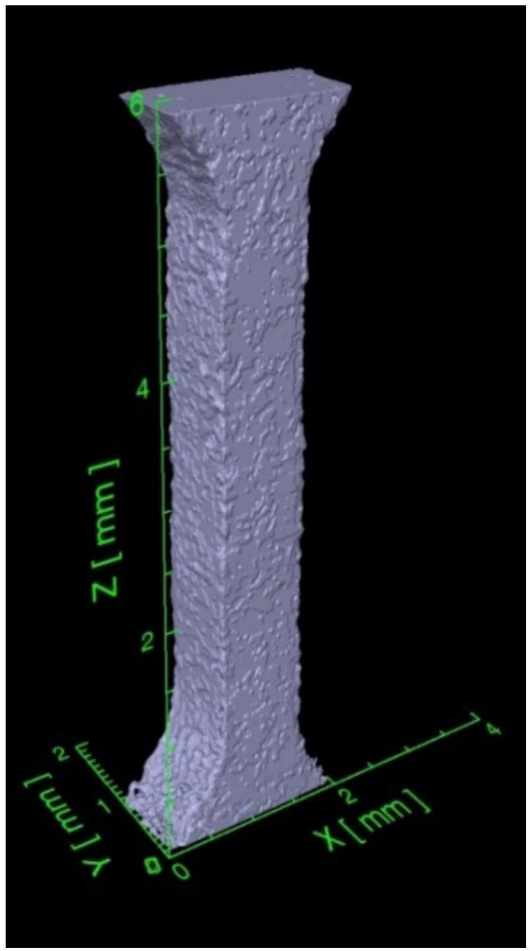
- While image processing has been a focus of considerable effort in the materials community, the sensitivity and impact of our segmentation decisions has not been routinely documented along with our results. Perhaps it should be.

- Multi-modal data holds significant promise for 3d studies however multiple measures of congruence are useful to resolve scale variations or inherent differences in data types

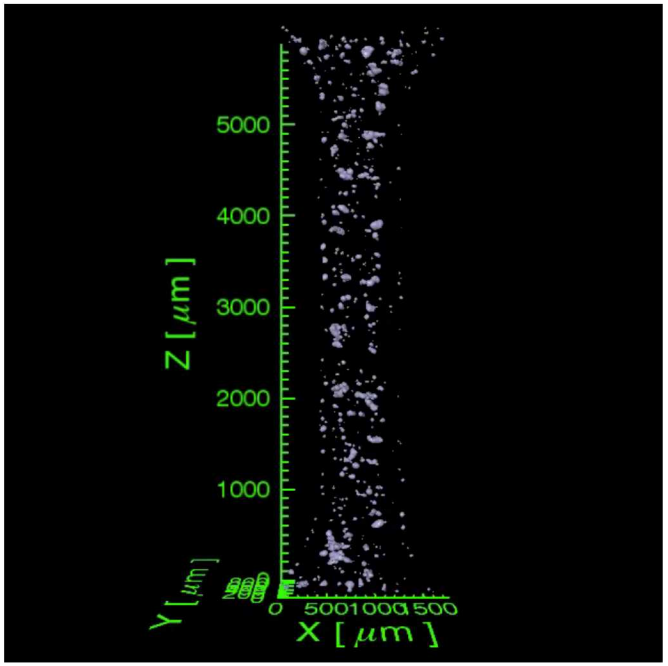
- It can be challenging to relate global or aggregate defect metrics to large-scale material performance in high ductility AM materials. However, 3D techniques already show promise for identification of localized failure modes even in AM metallic systems possessing high ductility

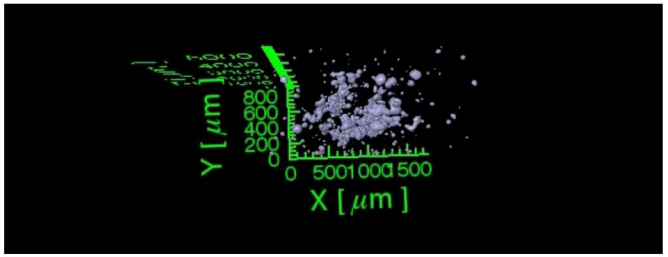
BACKUP SLIDES

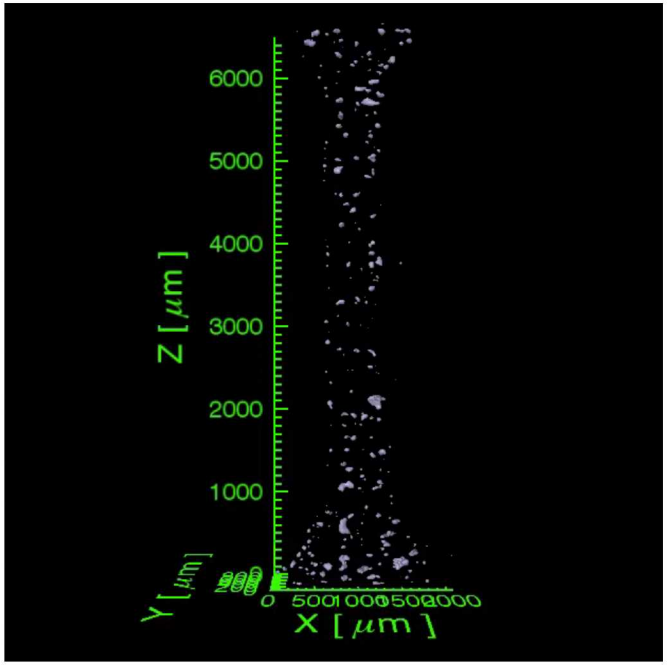
3D Reconstruction of Pore Defects

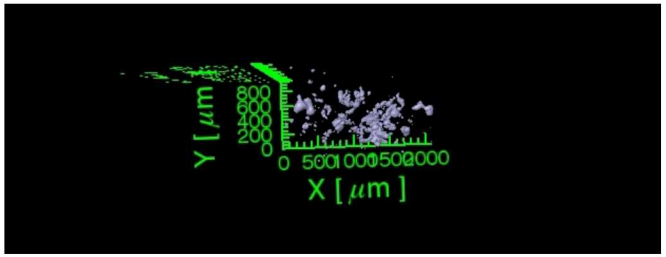


3D μCT surface render





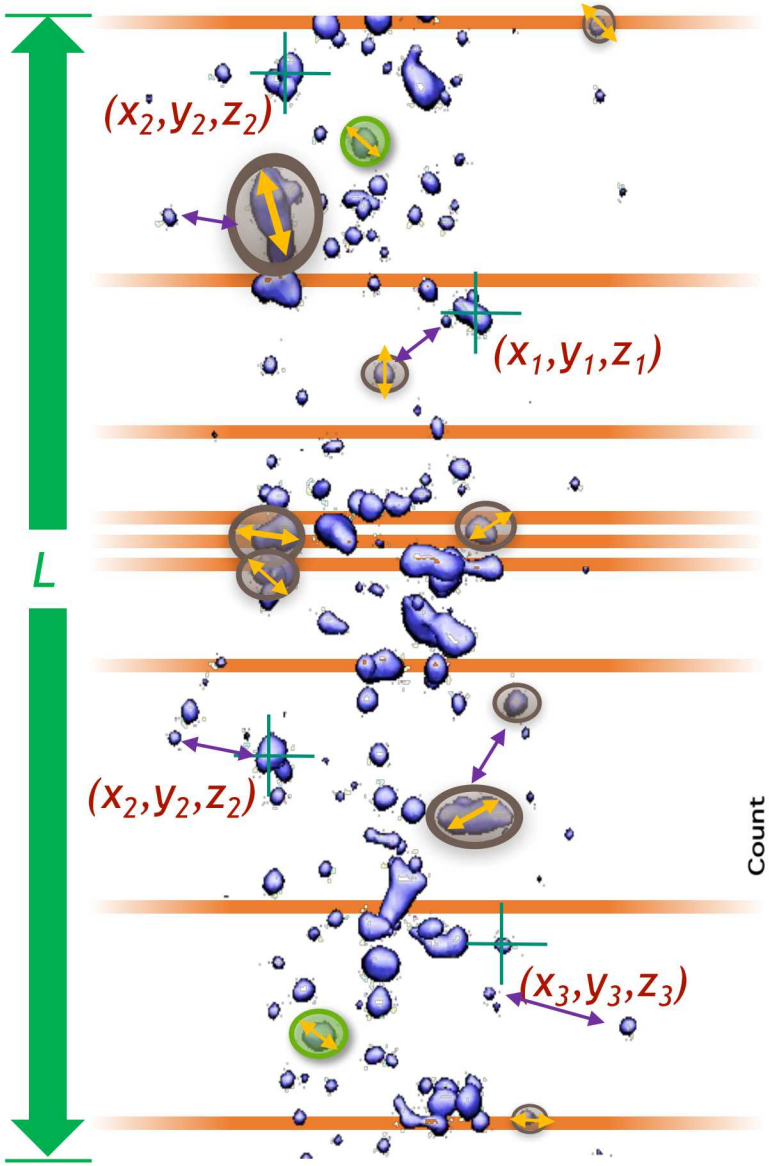




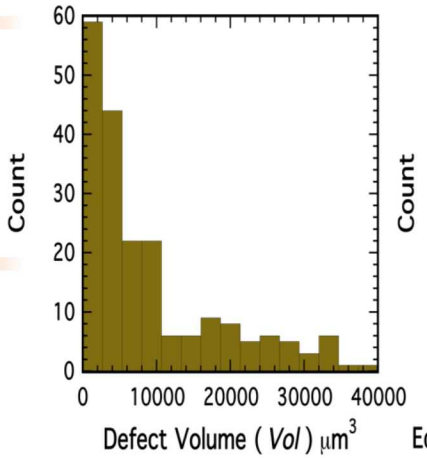
3D μCT internal porosity

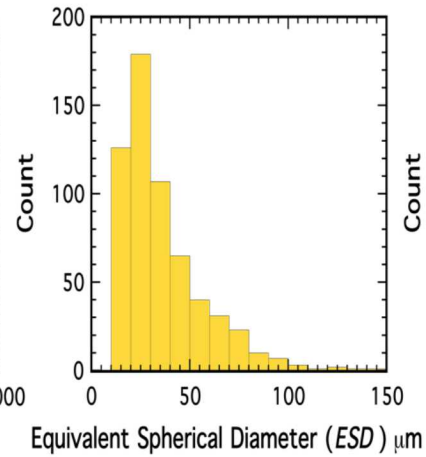
Tremendous variation in pore content from sample to sample
Pore locations reminiscent of AM laser raster pattern

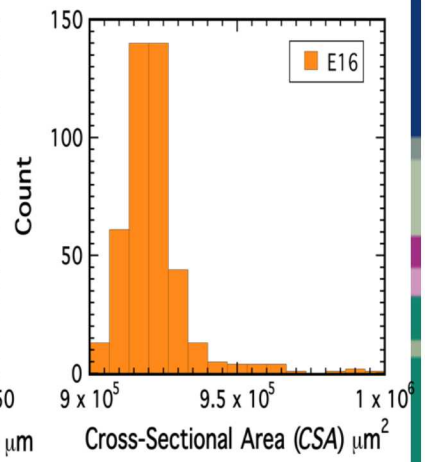
Defect Characterization



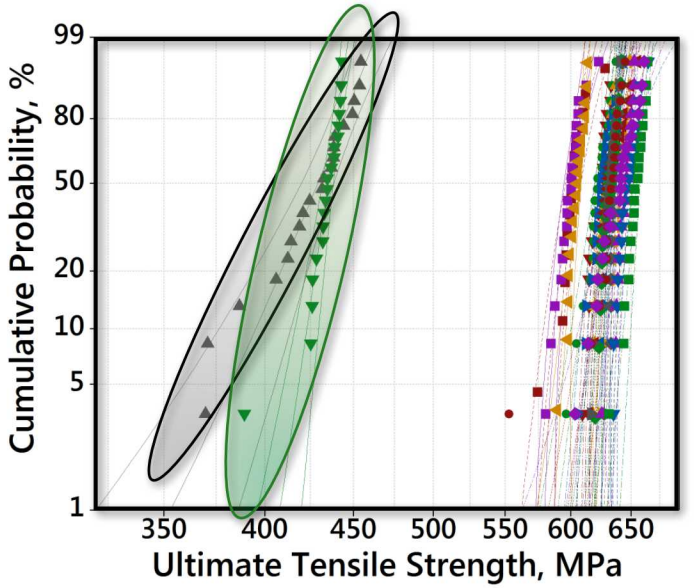
- Total Volume of Defects (V_{tot})
- Pore Volume Fraction (V_{fract})
- Spatial Location of Pores *(x, y, z)*
- Total Number of Defects *(N)*
- Total Defects/Length *(N/L)*
- Average Defect Volume ($V_{avg.}$)*
- Average Equivalent Spherical Diameter ($ESD_{avg.}$)*
- Average Cross-Sectional Area ($CSA_{avg.}$)*
- Average Nearest Neighbor Distance ($NND_{avg.}$)*

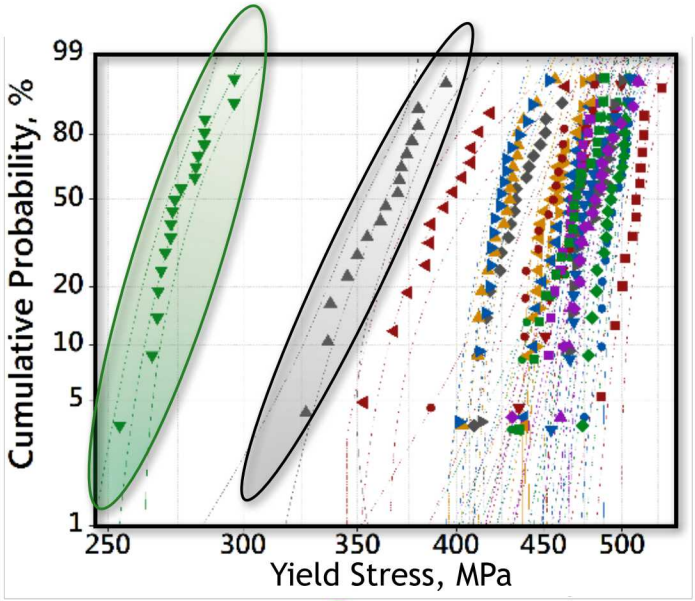


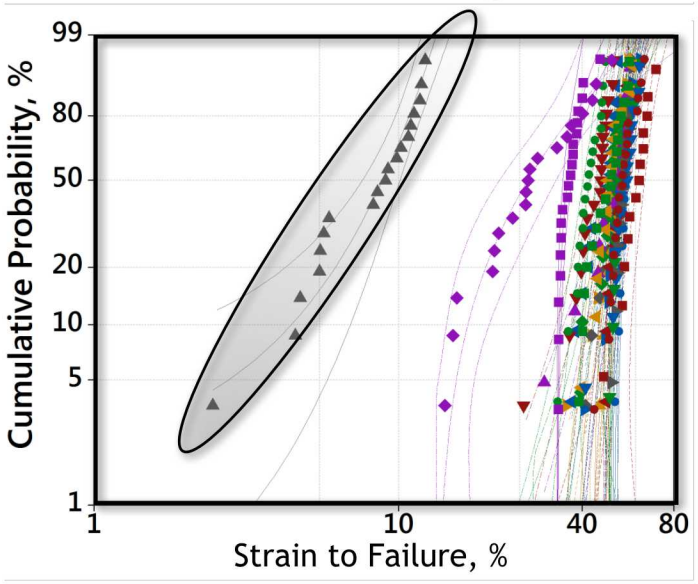


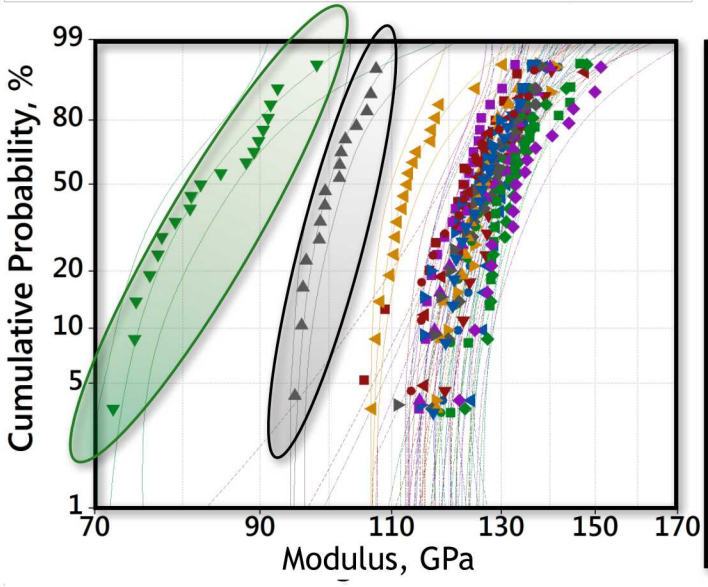


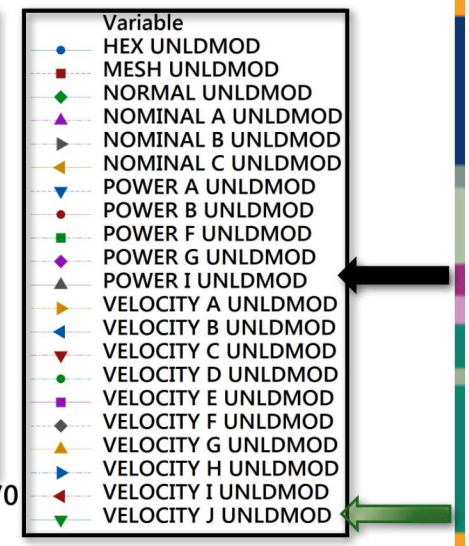
Process :: Properties





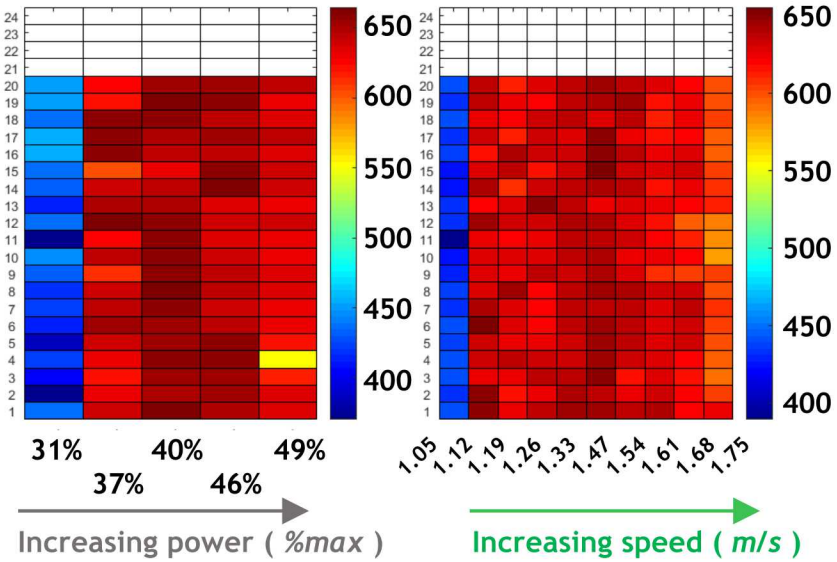




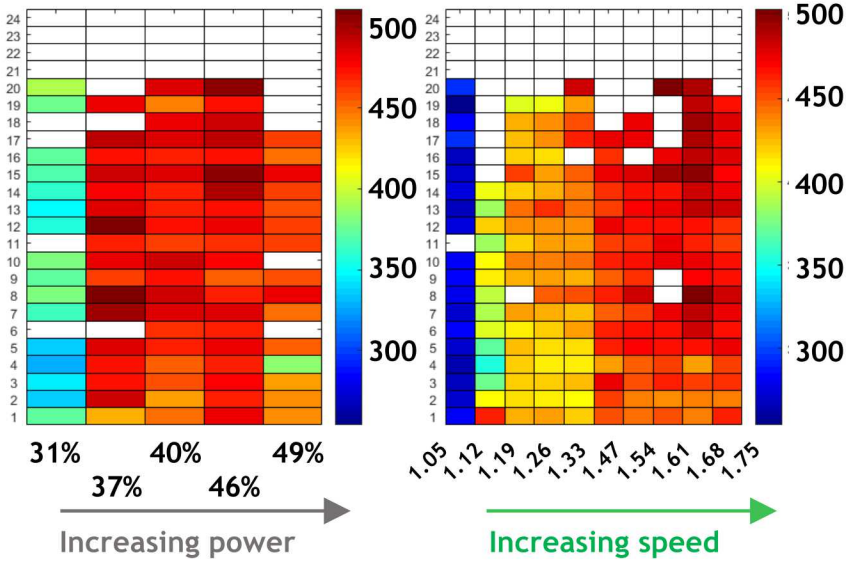


Process :: Properties

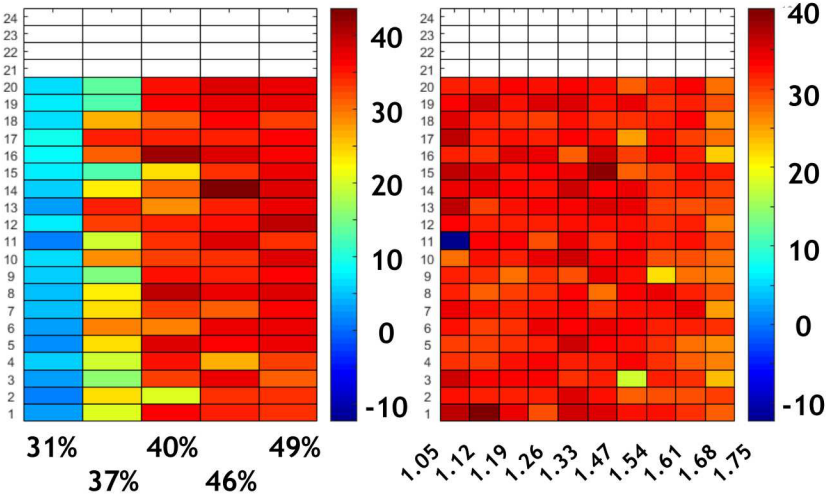
Ultimate Tensile Strength (MPa)



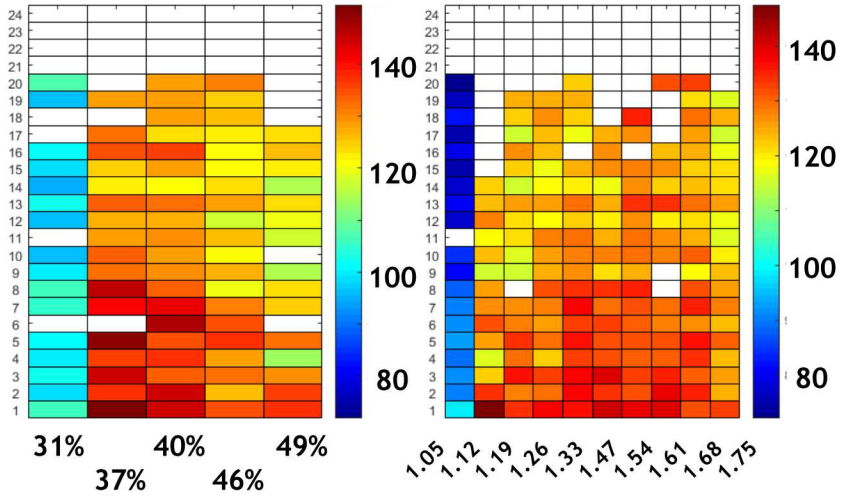
Yield Stress (MPa)



Elongation to Failure (%)



Modulus (GPa)



Process :: Structure :: Properties

R^2	Yield Stress (MPa)	Unloading Modulus (GPa)	Ultimate Tensile Strength (MPa)	Elongation to Failure (%)	Ductility (%)
Yield Stress (MPa)	1.00				
Unloading Modulus (GPa)	0.72	1.00			
Ultimate Tensile Strength (MPa)	0.79	0.83	1.00		
Elongation to Failure (%)	0.27	0.24	0.58	1.00	
Ductility (%)	0.11	0.12	0.45	0.91	1.00
Area (mm)	-0.75	-0.63	-0.50	0.09	0.22
Power (% max)	0.23	0.19	0.51	0.74	0.68
Velocity	0.59	0.38	0.27	-0.08	-0.24
Hatch Pattern	0.26	0.15	0.06	0.06	0.07
Density	0.27	0.38	0.68	0.72	0.62
Defects / Unit Length (mm^{-1})	0.49	0.32	0.56	0.48	0.39
Avg. Defect Volume (um^3)	0.32	0.24	0.11	0.06	0.27
Avg. ESD (um)	0.14	0.25	-0.06	-0.14	0.08
Total Defect Volume (voxels)	0.42	0.29	0.28	0.21	0.35
Volume of Dogbone (voxels)	0.11	-0.58	0.17	0.38	0.30
Defect Vol. Fract. - sample (%)	0.41	0.31	0.27	0.18	0.33
Defect Vol. Fract. - gage (%)	0.42	0.29	0.28	0.21	0.35

Material Properties

Processing Parameters

Defect Structure

- UTS, elongation & ductility exhibit notable correlations (~ 0.5+) with ***structure*** metrics such as density and pores / unit length.
- Likewise, UTS, elongation & ductility exhibit higher correlation (~ 0.5 - 0.7+) with ***processing parameters*** such as; laser power.
- Comparable relations are seen for scan velocity's impact on YS.