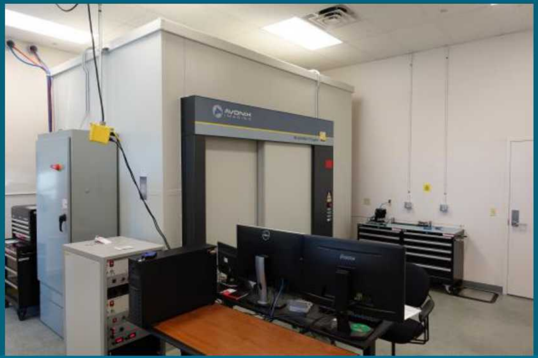
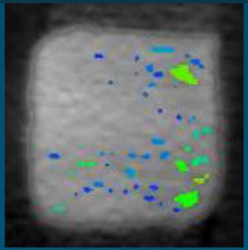
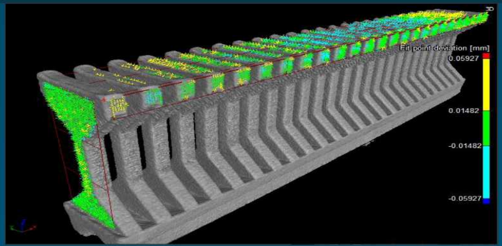
Sandia National Laboratories

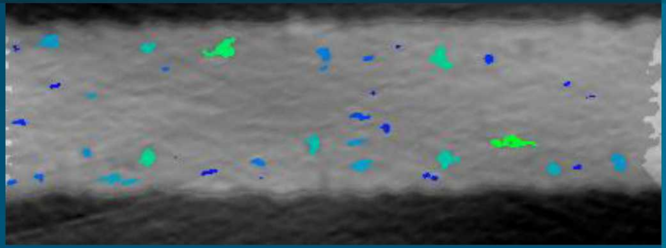
SAND2019-4478C

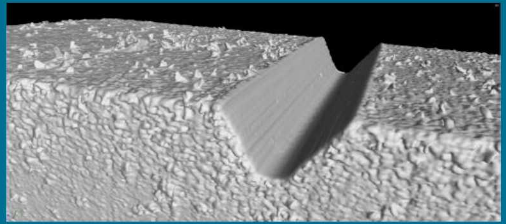
Spatial Energy Distribution Influences on the Detectability of Defects in Additively Manufactured Stainless Steel 316 Specimens

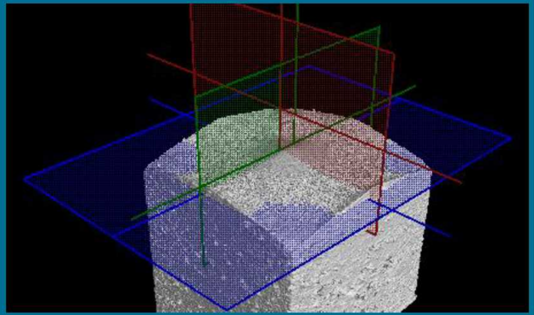












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ENERGY NNSA

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Outline

Additive Manufactured Sample Coupons (Dog Bone Arrays and Charpy Impact)

Introduction Computed Tomography and Evaluation Methodology

Porosity Analysis with: 1) VGEasyPore 2) VGDefX using 'General' Probability Settings and 3) VGDefX using 'Custom' Probability Settings

Comparison Region of Interest and Porosity Analyses

Mechanical Testing Results

Summary and Conclusions

Definitions

GED is defined as the ratio of the laser power (P) to the product of the laser speed (S) and hatch spacing (H), GED = P/(H*S).

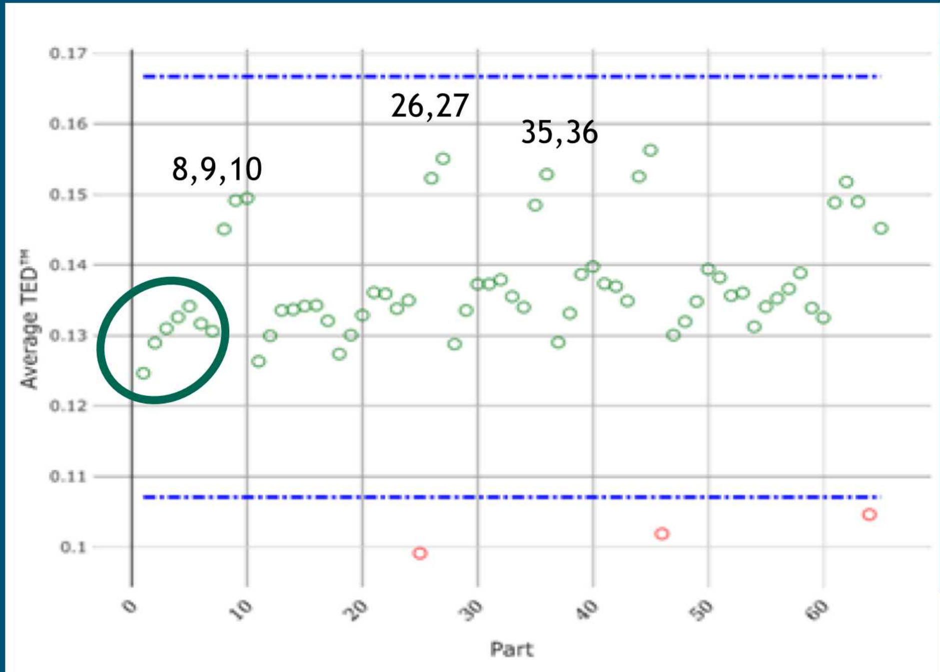
The GED is used to define the build range energy that creates optimal processing with the least amount of build porosity.

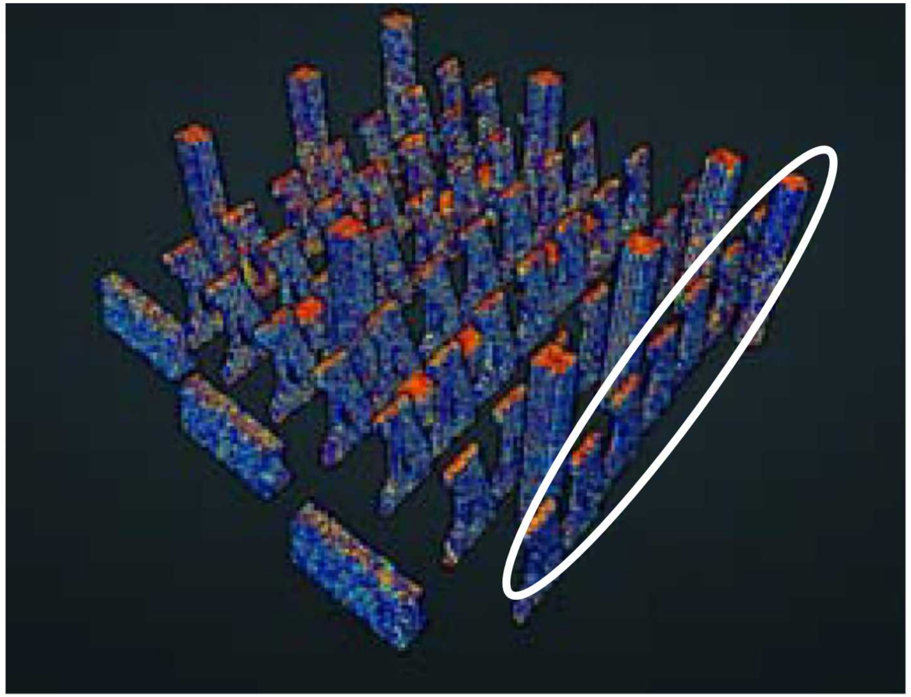
GED = (280 W)/[(0.14 mm)(1200 mm/sec)] = 1.67 J/mm^2

TED™ (Thermal Emission Density) is a proprietary metric of Sigma Labs. It is a dependent in-process data measurement that is collected from the photodetector. It tracks and measures changes in laser power level (energy per area).

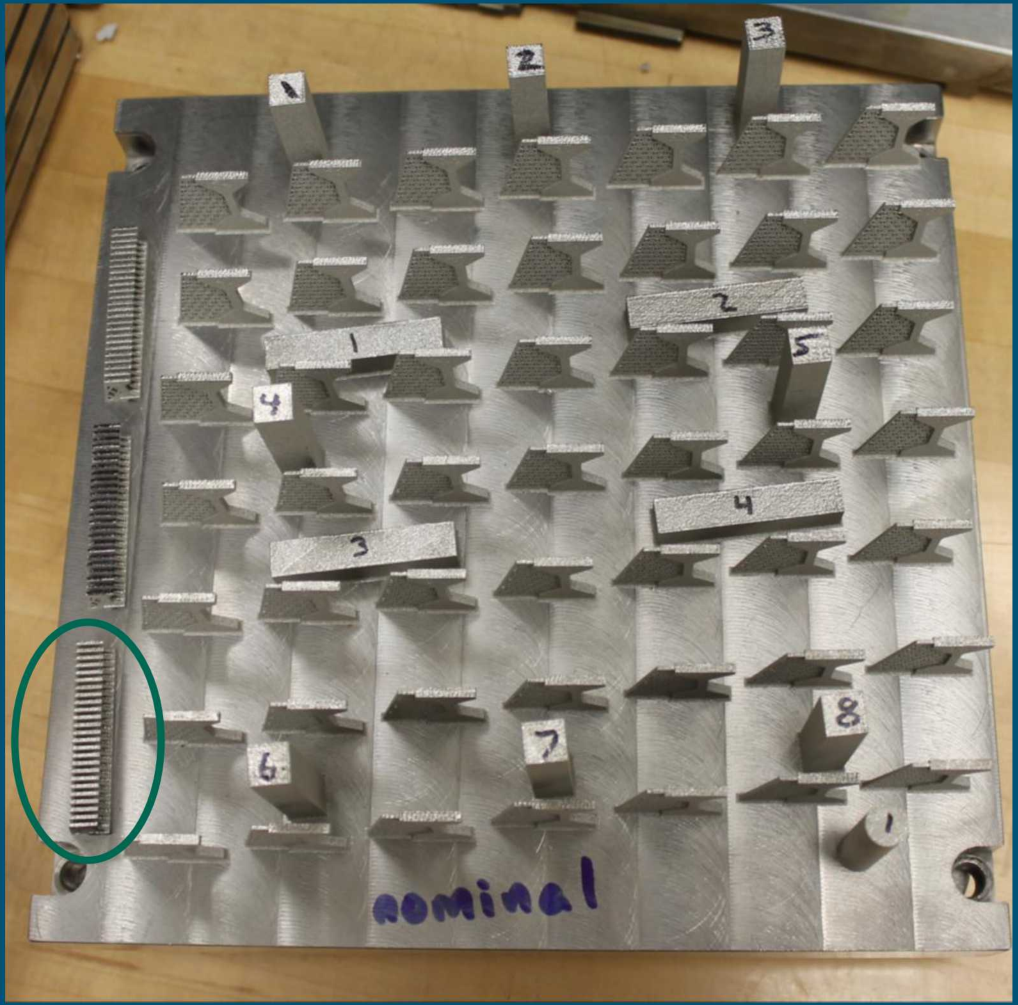
As S ⬆ and P ⬇ energy density is lower. This creates loss of melting of the powder and angular shaped voids (lack of fusion).

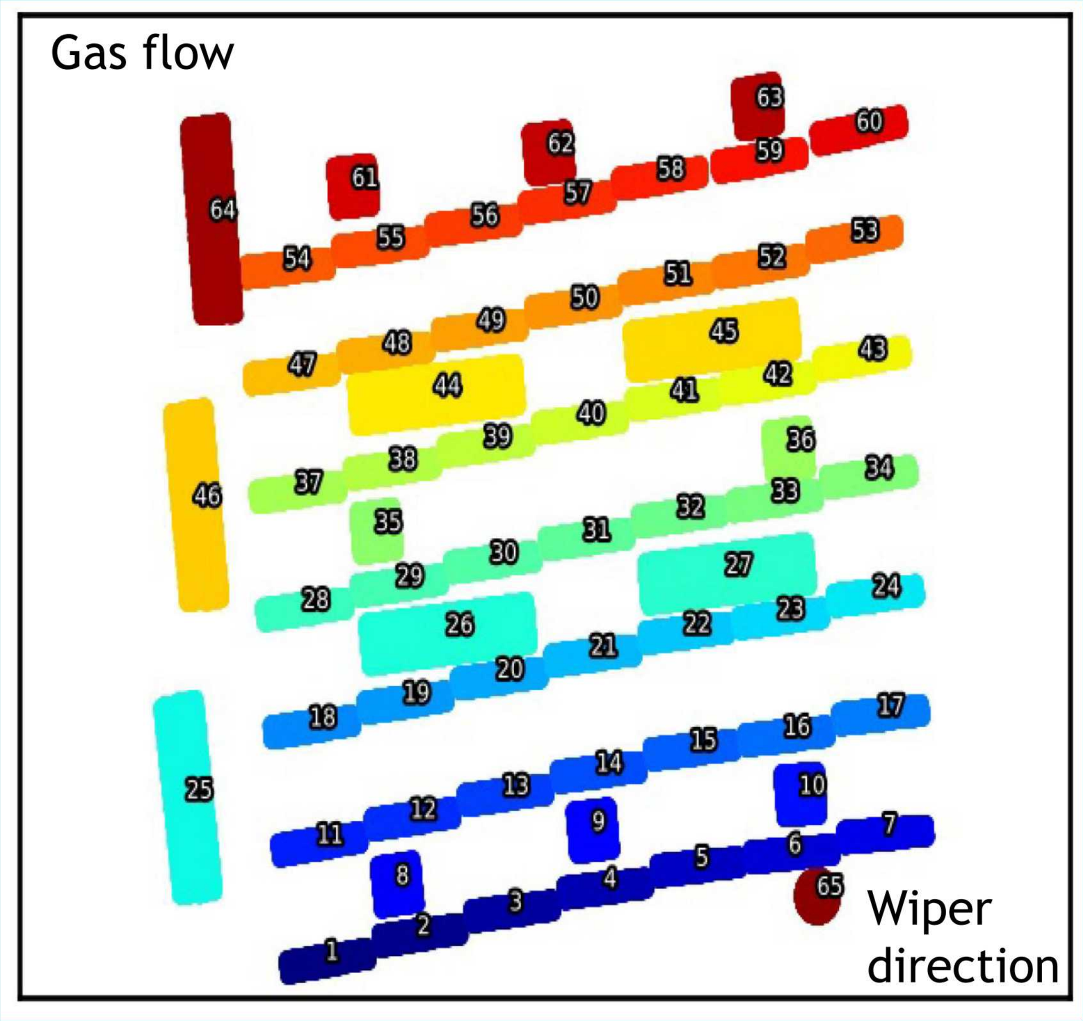
As S ⬆ and P ⬇ energy density is elevated. This creates voids and spherical porosity. There is a energy density that melts powder and maintains optimized depth to width ratio where defects will be minimized.





Build Layout





Samples on build plate: 8 Vertical Charpy; 4 Horizontal Charpy; 75 A-size tensile 42 B-size tensile

Focus of the Study: AM 25 Tensile Coupons

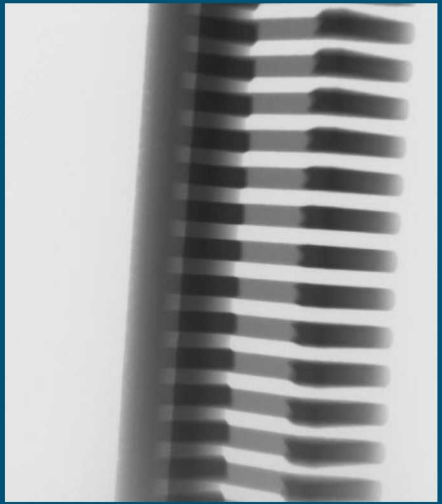
Specimen Geometry:

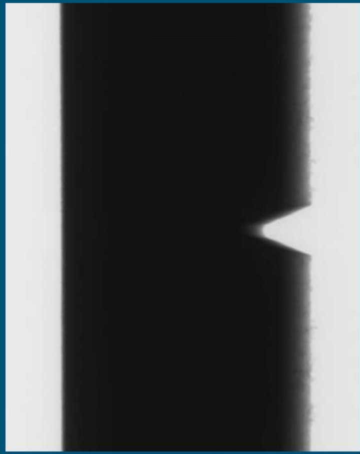
75 Tensile Test Coupons (Dog Bones)
30 Charpy Impact Coupons

Sample Material: Stainless Steel 316-L
Produced on: EOS 290 Machine
Post Processing: None

Build Parameters: Particle size 30 - 60 um Stainless Steel 316 -L, 400W IPG Photonics Laser.

X-Ray Parameters: 440 kV, 227 µA, 1 mm Copper Filter
Scan Parameters: Helical Scan
Reconstruction from 2294 Projections at 8 frames/projection





CT - Images

Identify porosity in the gage regions of the dog bones and the notch area.

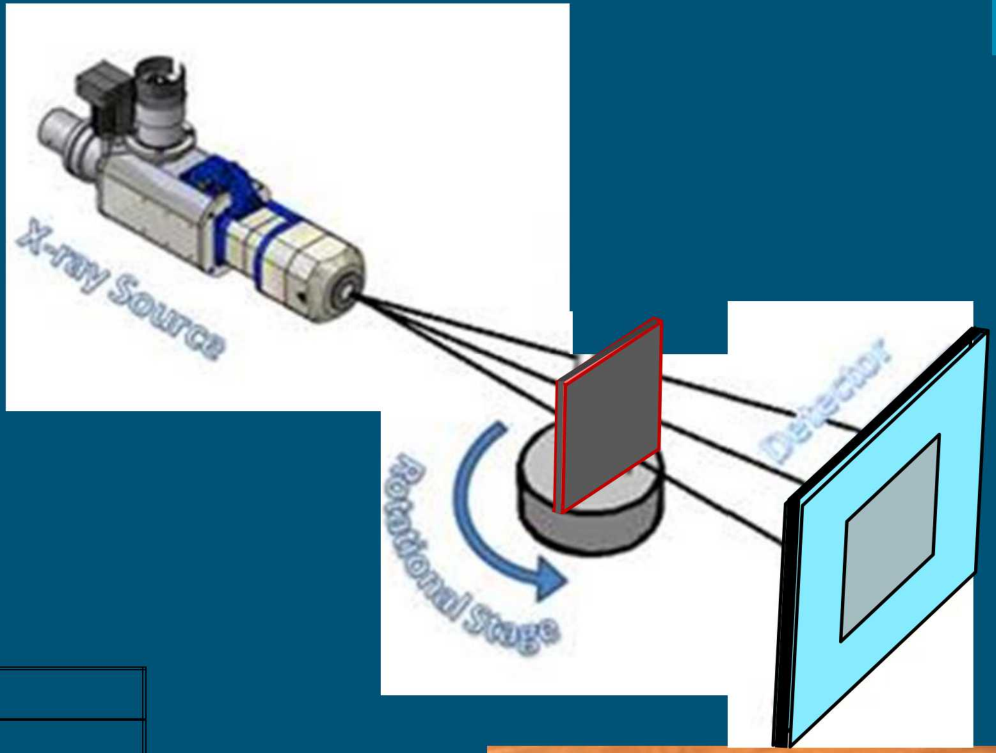
Compare built-in techniques for identifying porosity. Quantify any correlation between both build direction and/or gas flow direction and the identified porosity.

Correlate inspection data to mechanical properties.

A helical scan effectively removes some types of image artifacts and allows acquisition of a single volume of elongated data. This technique helps optimize the technique with low aspect ratio parts (dog bones). The created sinograham eliminates circular artifacts. The scan time can be reduced dramatically while resolution is increased.

Computed Tomography: Set-up

- Penetrating radiation is attenuated by the AM material.
- A digital sampling of the radiation that hits the detector is collected.
- Multiple images are taken at different angles while the part is spun 360 degrees.
- The two dimensional images are reconstructed into a three dimension data sets that can be sliced in the XY, YZ, or XZ planes.



Sample	***316L Stainless Steel (dog bone array)***		
Energy	***440 KeV***	**Projections**	***2294***
Watts	***99.88 W***	**Effective Pixel Size**	***10 µm***
Magnification	***~ 13 X***	**Detector Type**	***Perkin Elmer***
Filter	***1 mm Cu***	**X-ray Head Type**	***Nikon 450kV, M2***
Time	***2 hours***	**Frame Average**	***8***

Sample	***316 Stainless Steel (Charpy Impact)***		
Energy	***225 KeV***	**Projections**	***1200***
Watts	***9.3***	**Effective Pixel Size**	***24 um***
Magnification	***~ 84.5 X***	**Detector Type**	***Varian***
Filter	***1 mm Cu***	**X-ray Head Type**	***Varex***
Exposure Time	***2 hours***	**Frame Average**	***1***

Computed Tomography: Parameter Optimization

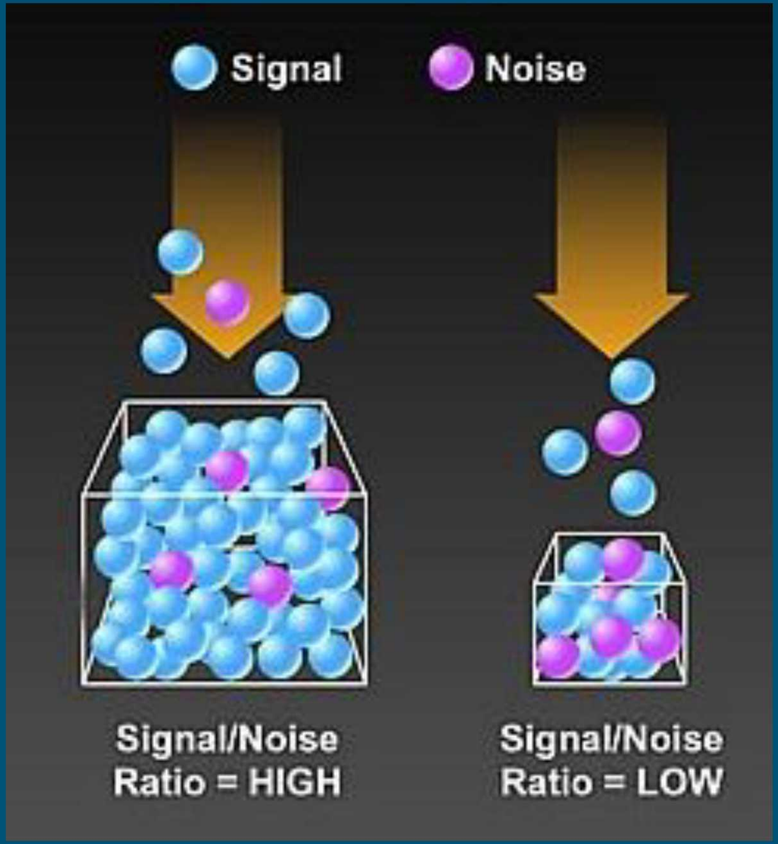
Before data analysis is conducted artifacts must be identified and reduced.

Higher Signal to Noise Ratio through Artifact Reduction

- Beam Hardening and Under Sampling
- Cone Beam
- Unsharpness
- Motion and Centering
- Ring

Higher Resolution through Smaller Detector Pixels

- More pixels per sample area = higher resolution images
- Less sensor area = increased sampling times
- Smaller focal spot sizes = less x-ray power



Source: nikonian.com

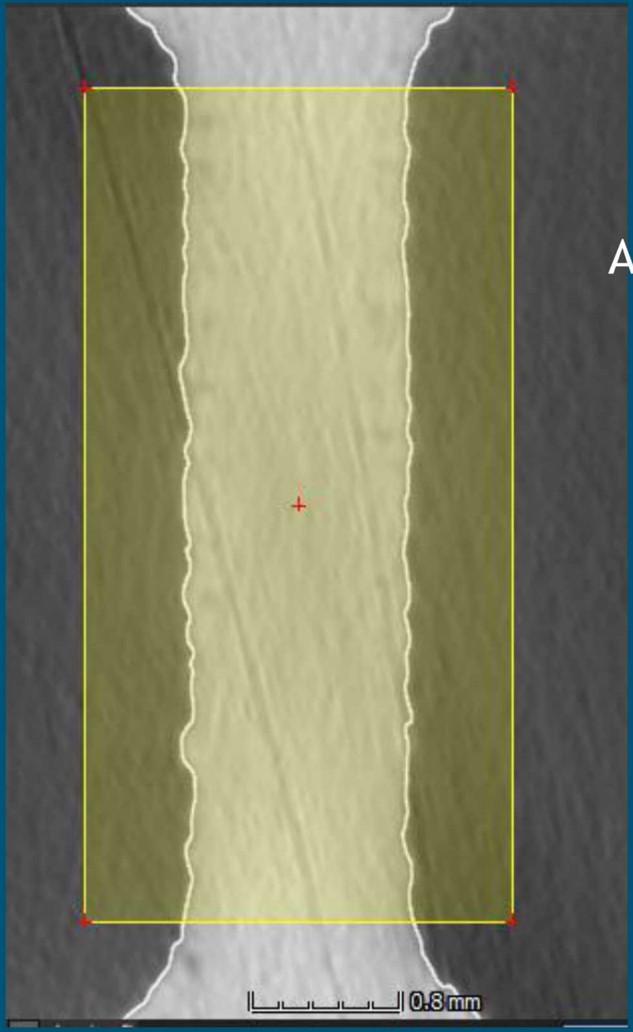
Evaluation Methodology: Isolate Gage Regions:

Why:

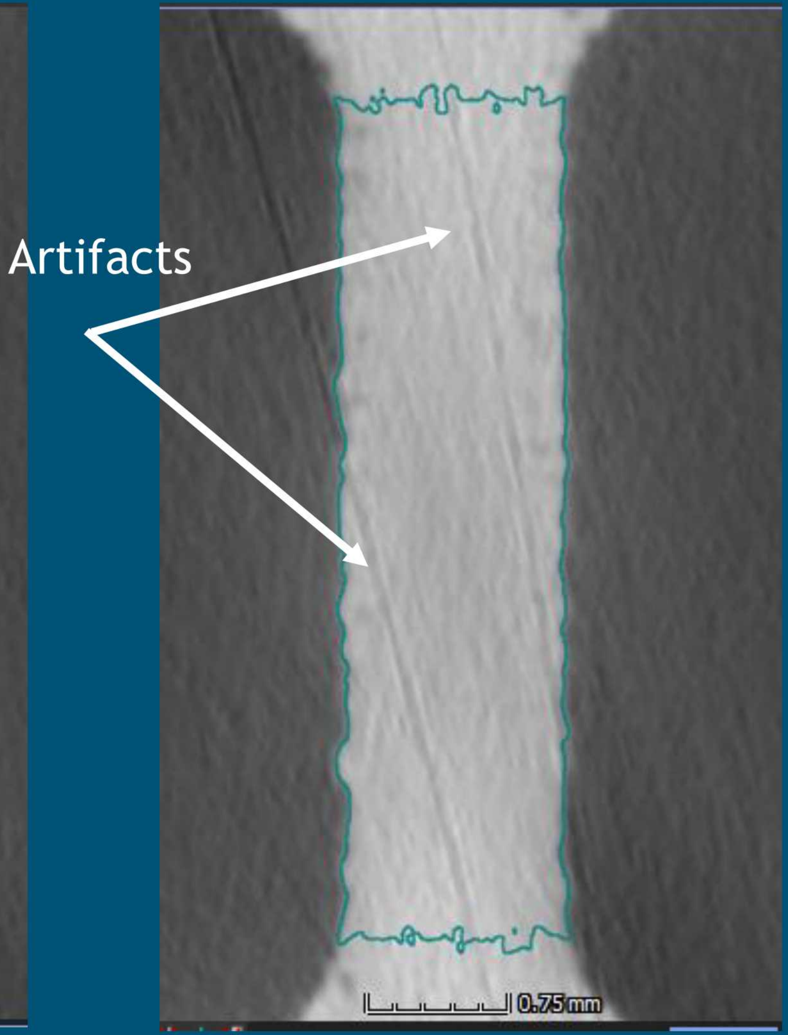
- Failure of (dog bone) tensile coupons occurs in the gage region between the upper and lower tabs.
- Area of greatest interest is at the gage region of the part.

How:

- Create rectangular ROI (RectROI).
- Intersect RectROI with the ROI from the surface determination.
- Opening volume by 2 voxels using a spherical structured element to remove internal voids (dilation then erosion)
- Closing volume by 2 voxels using a spherical structured element to remove external noise (erosion then dilation)
- Refine surface with translation along surface normal to optimal location. Search distance was set to 0.1198 mm



Define RectROI



Final Isolated Gage Region

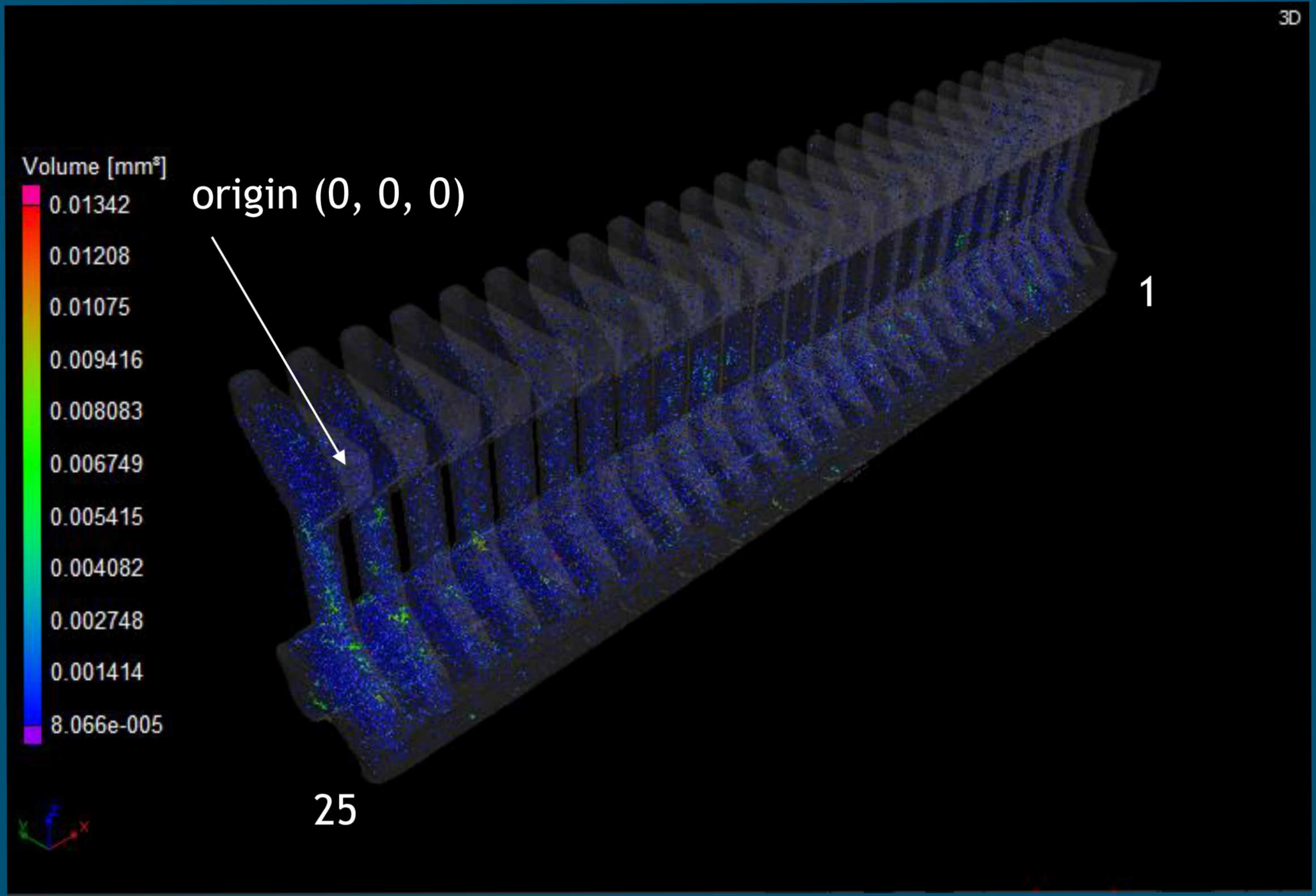
Evaluation Methodology: VGEasyPore

Local contrast controlled porosity identification:

- Local contrast mechanism reduces the need for isolated ROI for analysis.

Parameter Settings

- Contrast: 203
- Local area size [vox]: 10
- Analysis area: Internal cleaning, small (no closing)
- Surface sealing: 2 voxels

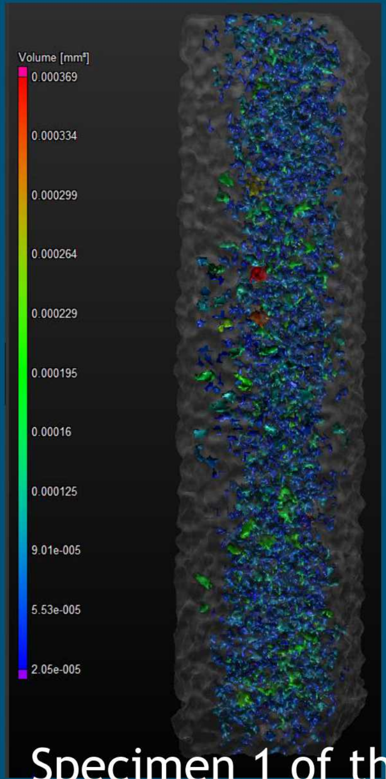


Results: Parameter Dependence

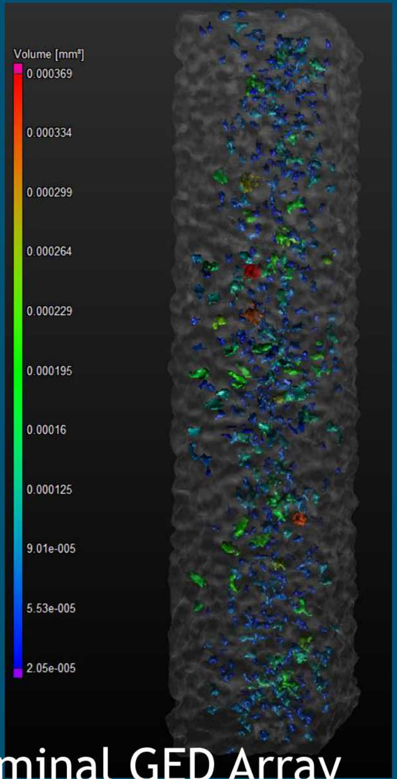
Probability Dependence:

- Filtering the results based on probability of detection has a large effect on the total number of pores found (voxel based).

Probability Threshold: 0.00



Probability Threshold: 0.85

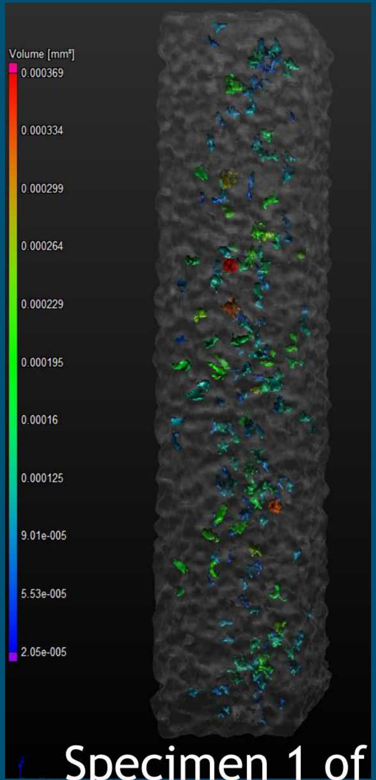


Specimen 1 of the nominal GED Array

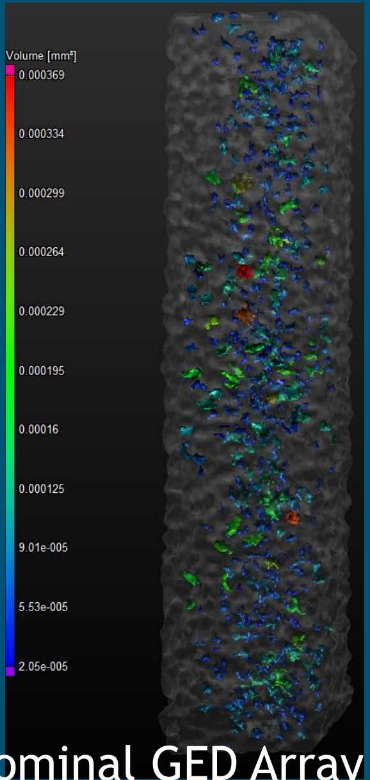
Diameter Dependence:

- Filtering the results based on pore diameter can be used to specifically remove small pores believed to be the result of noise in the scan volume or of insignificant size compared to the large defects.
- Minimum diameter as 1/10 of the max size vs min size as ~4 voxels wide for detection

Min: 0.1 Max: 1.00



Min: 0.0625 Max: 1.00



Specimen 1 of the nominal GED Array

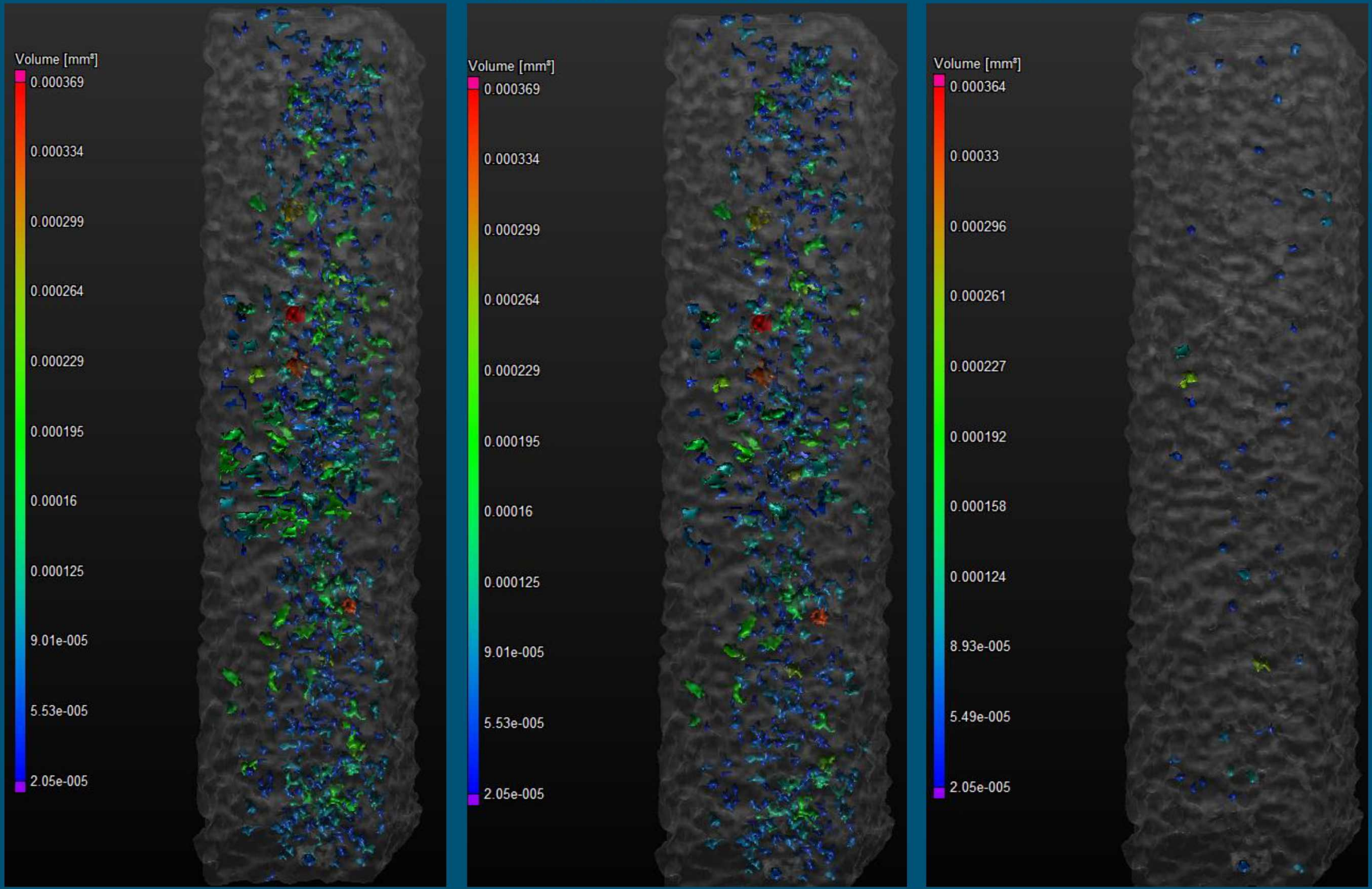
Results: Parameter Dependence

Compactness Dependence:

- Compactness: the ratio of the pore/defect volume to the volume of its circumscribed sphere.
- Filtering the results based on compactness helps to reduce the prevalence of long and thin pores that commonly result from noise in the scanned volume.
- Raising the minimum compactness too high can easily filter out large and significant pores due to their complex geometry.

Specimen 1 of the nominal GED Array

Min: 0.00 Max: 1.00 | Min: 0.08 Max: 1.00 | Min: 0.25 Max: 1.00

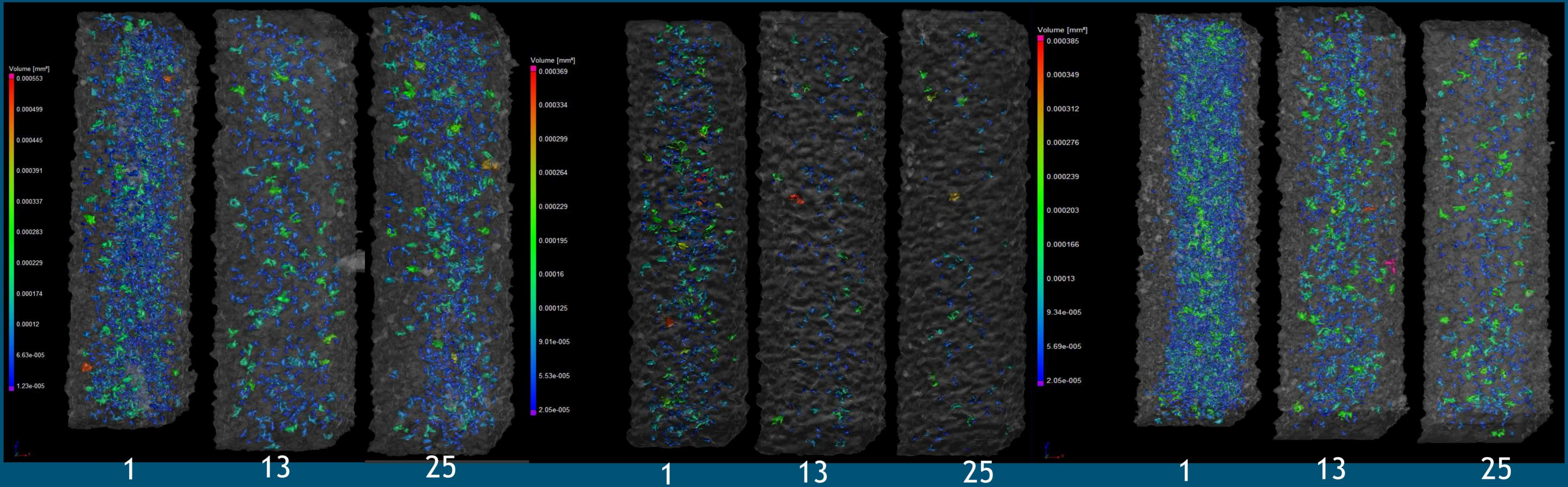


Porosity Results for all Three High GEDs

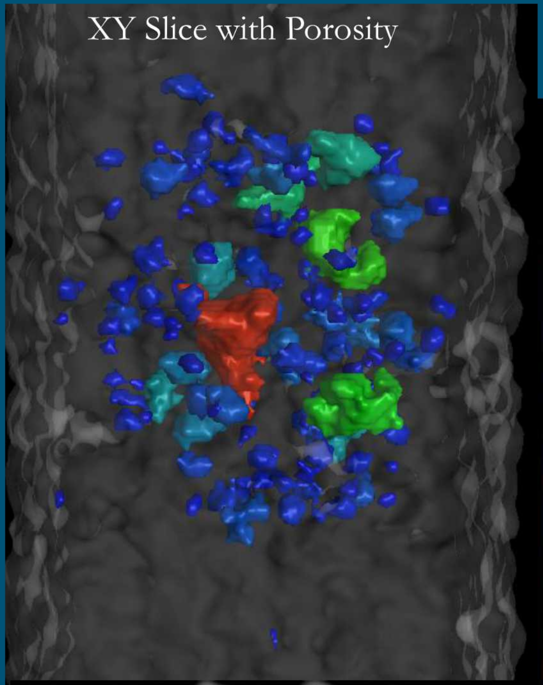
High GED: Specimen 1 has a larger void percentage with most counts under 2%. Specimen 13 has larger void sizes than sample 1. There is less voids near the center of the sample. Specimen 25 has largest void percentage.

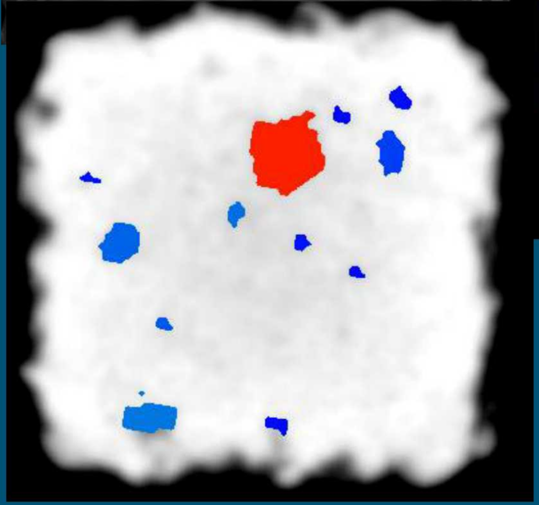
Nominal GED: Specimen 1 has a larger void percentage with most counts under 6%. Specimen 13 has larger void sizes with less smaller ones. There is less voids near the center of the sample. Specimen 25 extremely low void percentage.

Low GED: Specimen 1 has larger void percentage with most counts under 3%. Specimen 13 has larger pores. Specimen 25 has lower porosity distributed throughout the volume. Medium to small porosity sizes dominate this part.

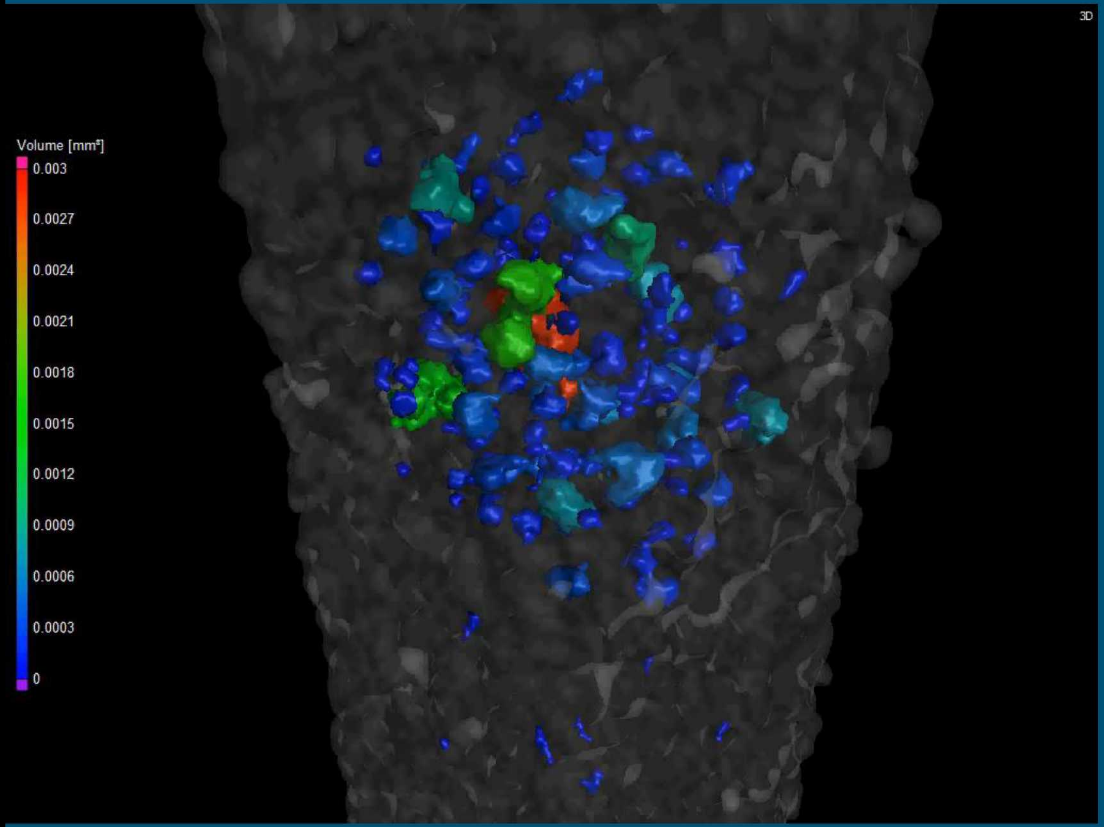


Porosity Analysis at a Failure Location

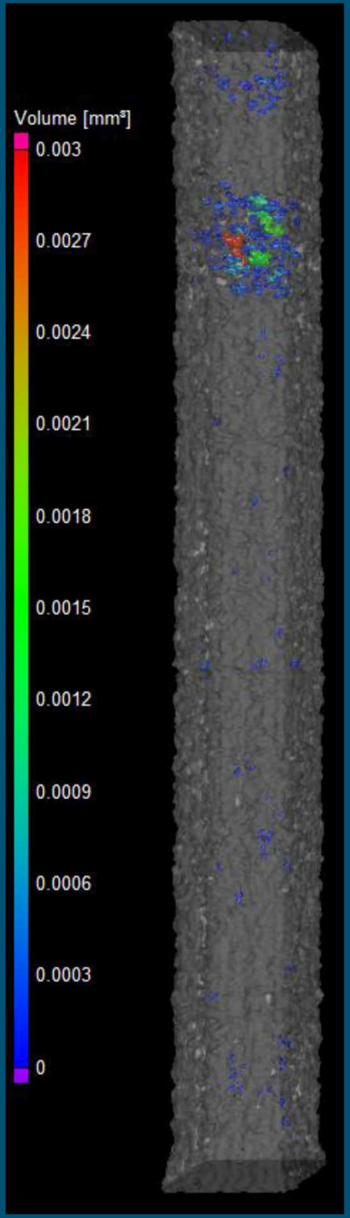




Distribution and Density



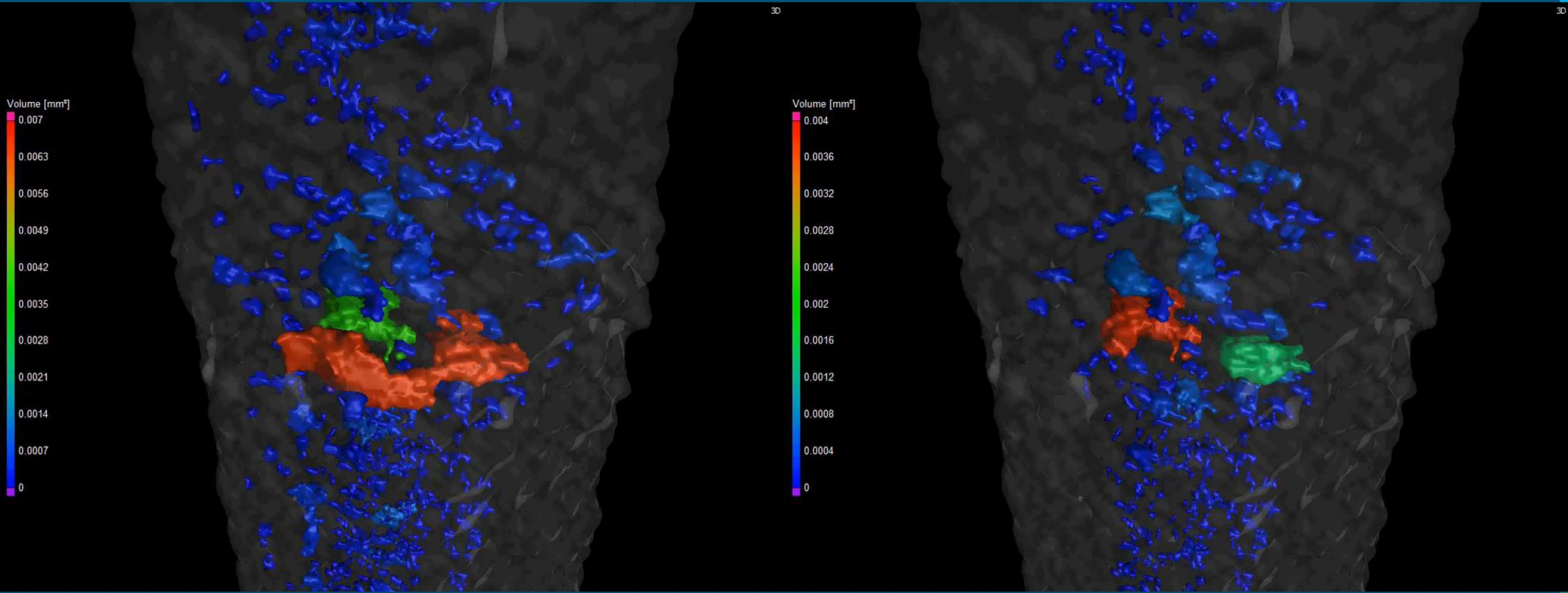
- Pore Volume
- Location
- Sphericity
- Diameter



If large pores are surrounded by numerous smaller pore groups failure will occur in this region. Note: the build was stopped and resumed. Material cooling effects created porosity accumulation.

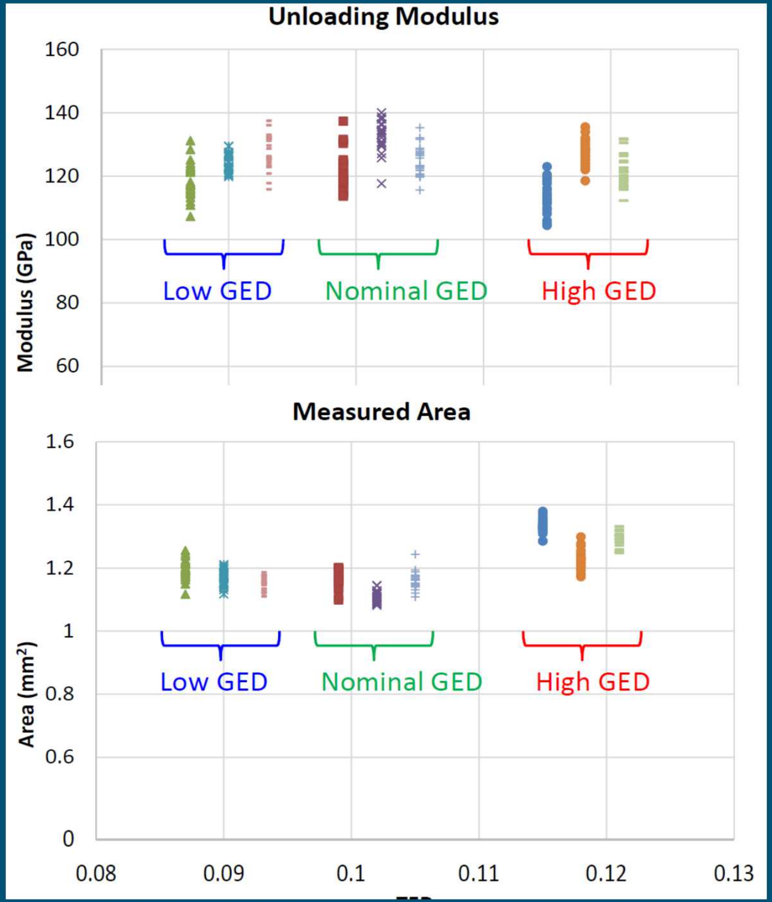
Porosity Analysis Using Different Input Parameters

Changing the way porosity is detected using the above functions can effect the rendered solution but not the fracture location.

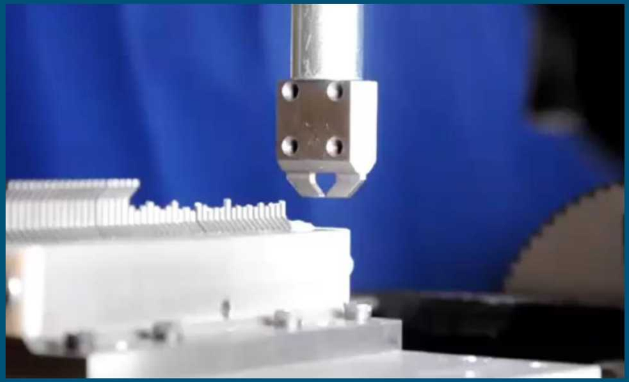


Mechanical Tensile Testing

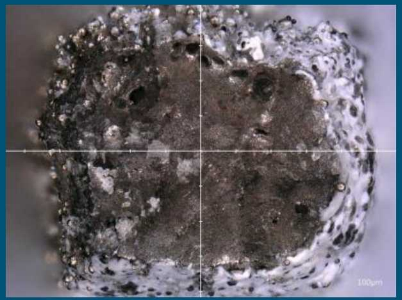
Modulus (Gpa)

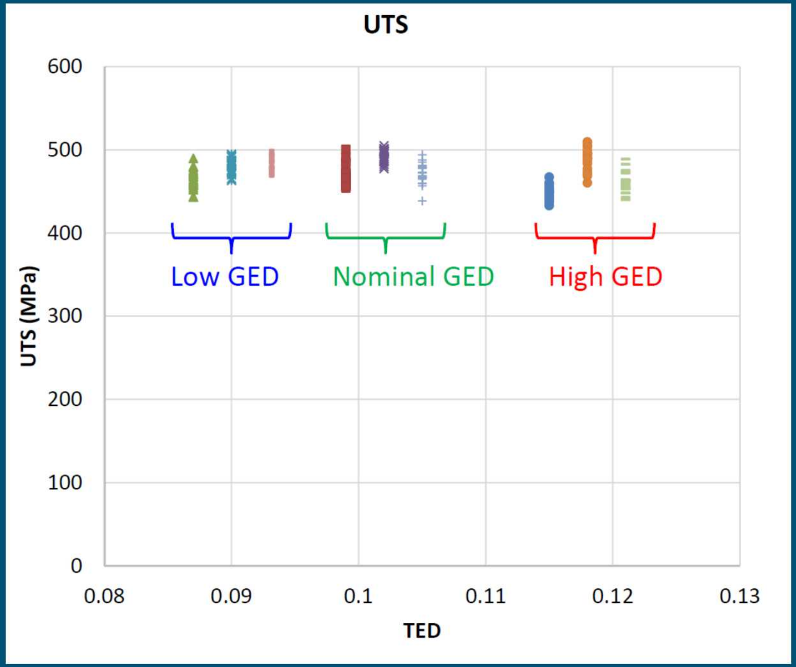


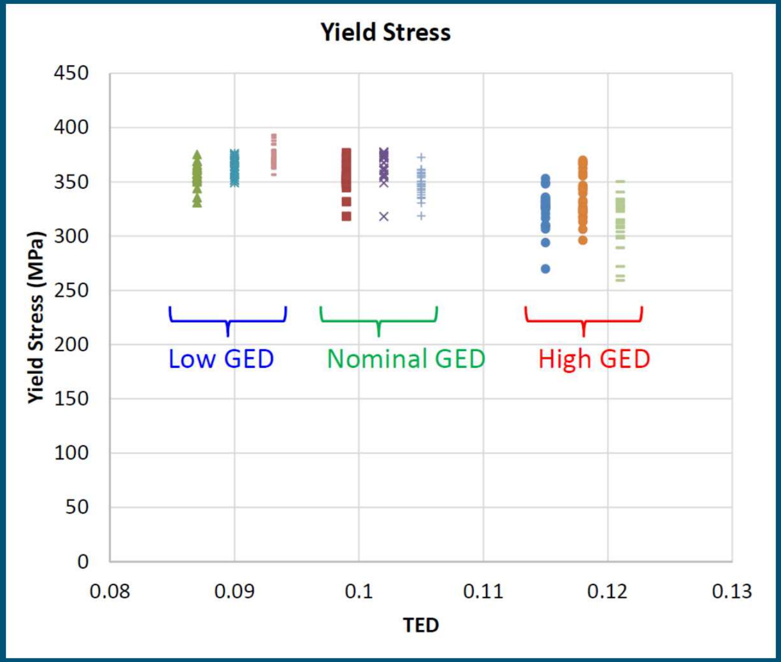
The modulus of the three build plates (Low, Nominal and High GED) is roughly equivalent. Measured area is typically larger than the effective cross sectional area due to; surface roughness, crust, and porosity. The effective area can be calculated by an adjustment based on the measured unloading modulus compared to the "true" ultrasound modulus.



The High GED specimens (high TED values) have slightly lower yield strength. Surface roughness is impacting the cross section.

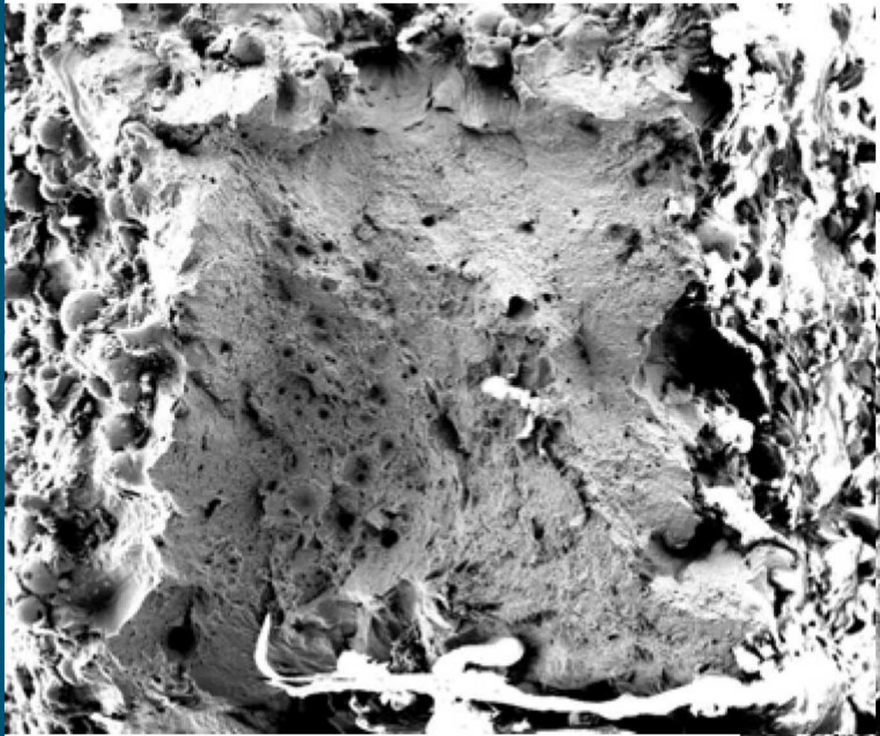






Fractography of Tensile Samples

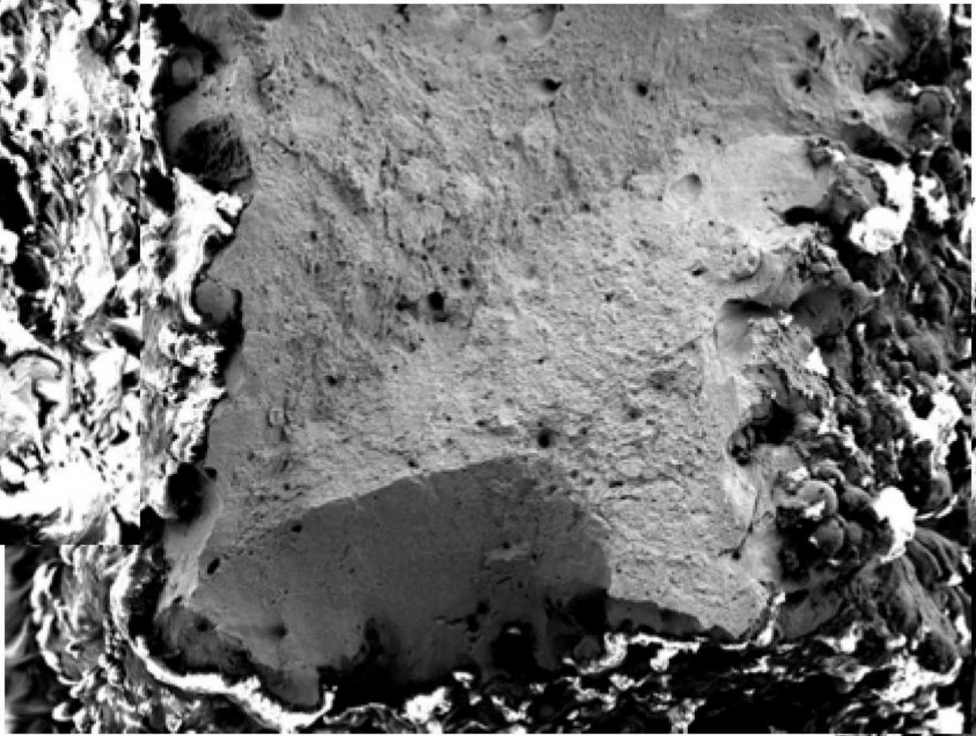
Low



Fractography and CT scanning show that Low GED specimens have more porosity

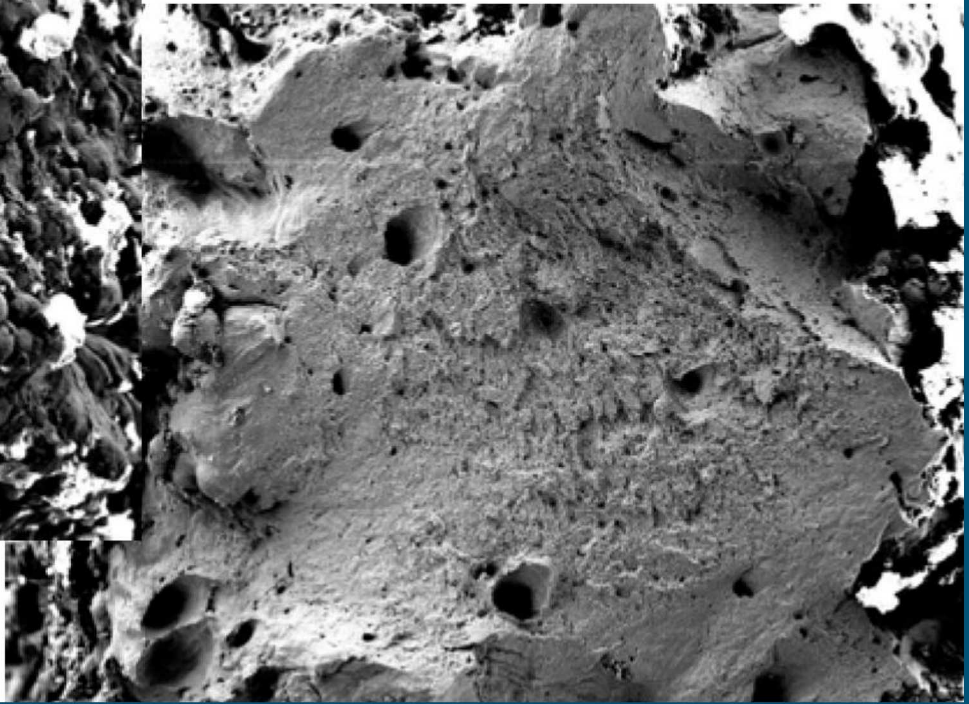
Nominal

Fractography and CT scanning show that the nominal specimens have the least porosity



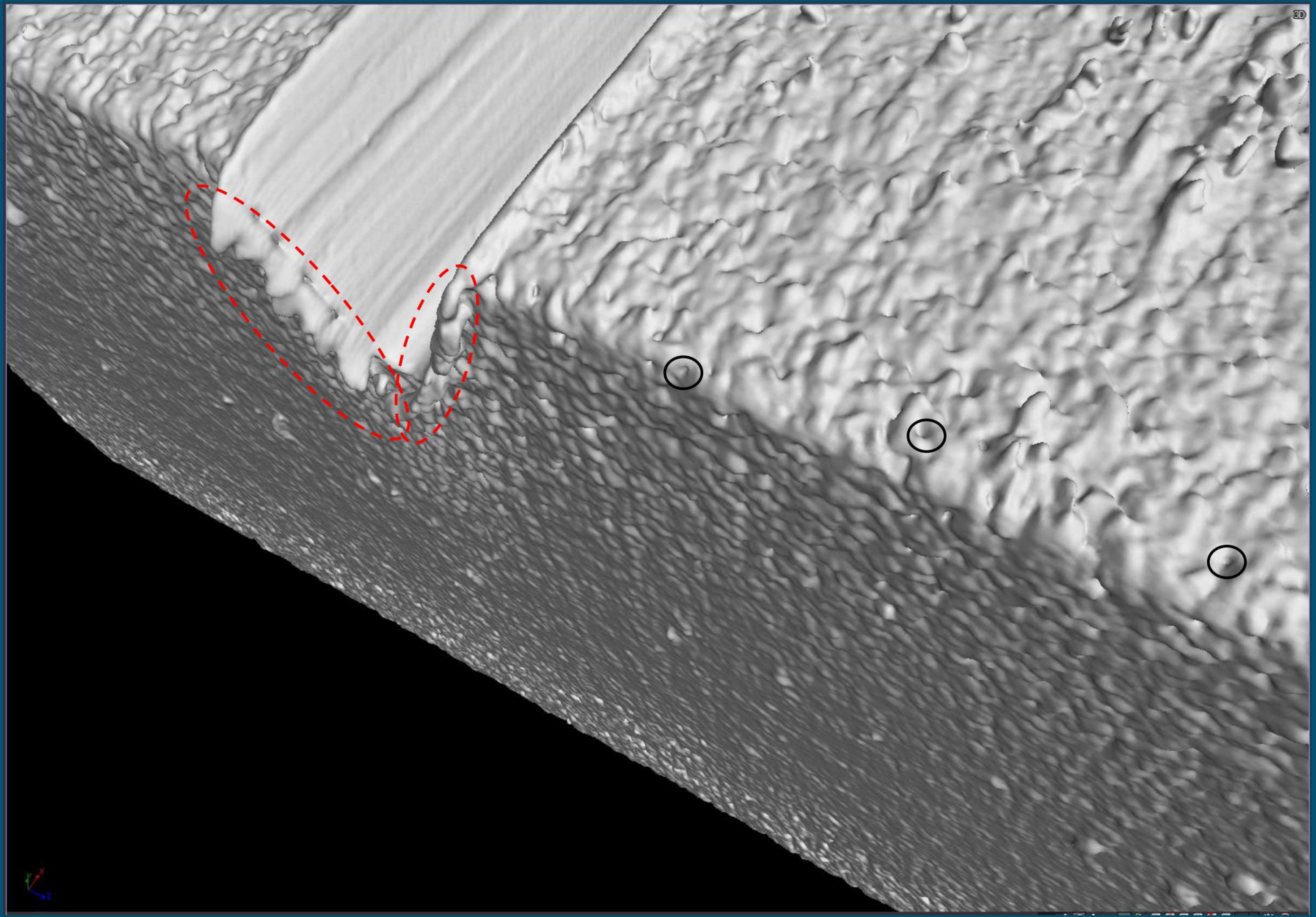
High

Fractography and CT scanning show that High GED specimens have more porosity



Surface Topography

Surface Roughness and Burr Identification:

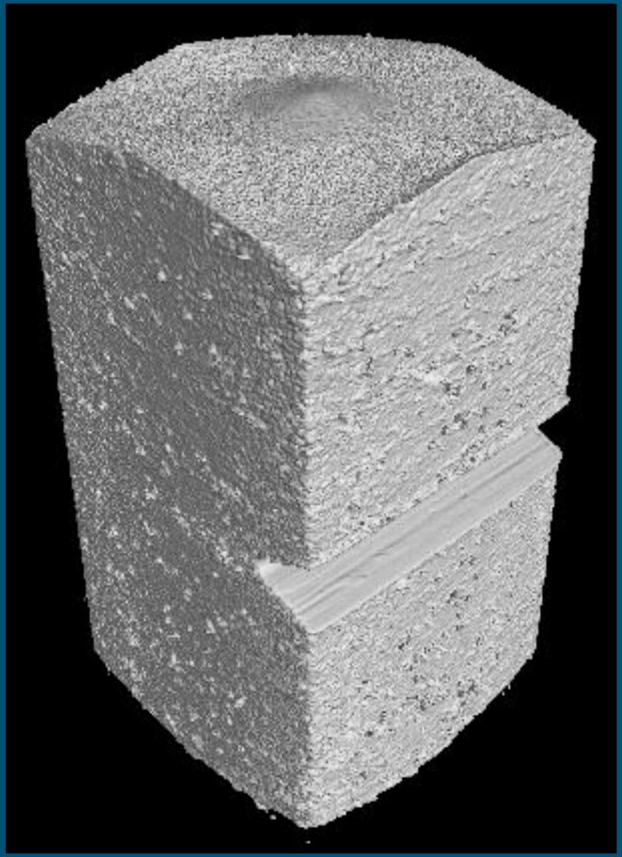


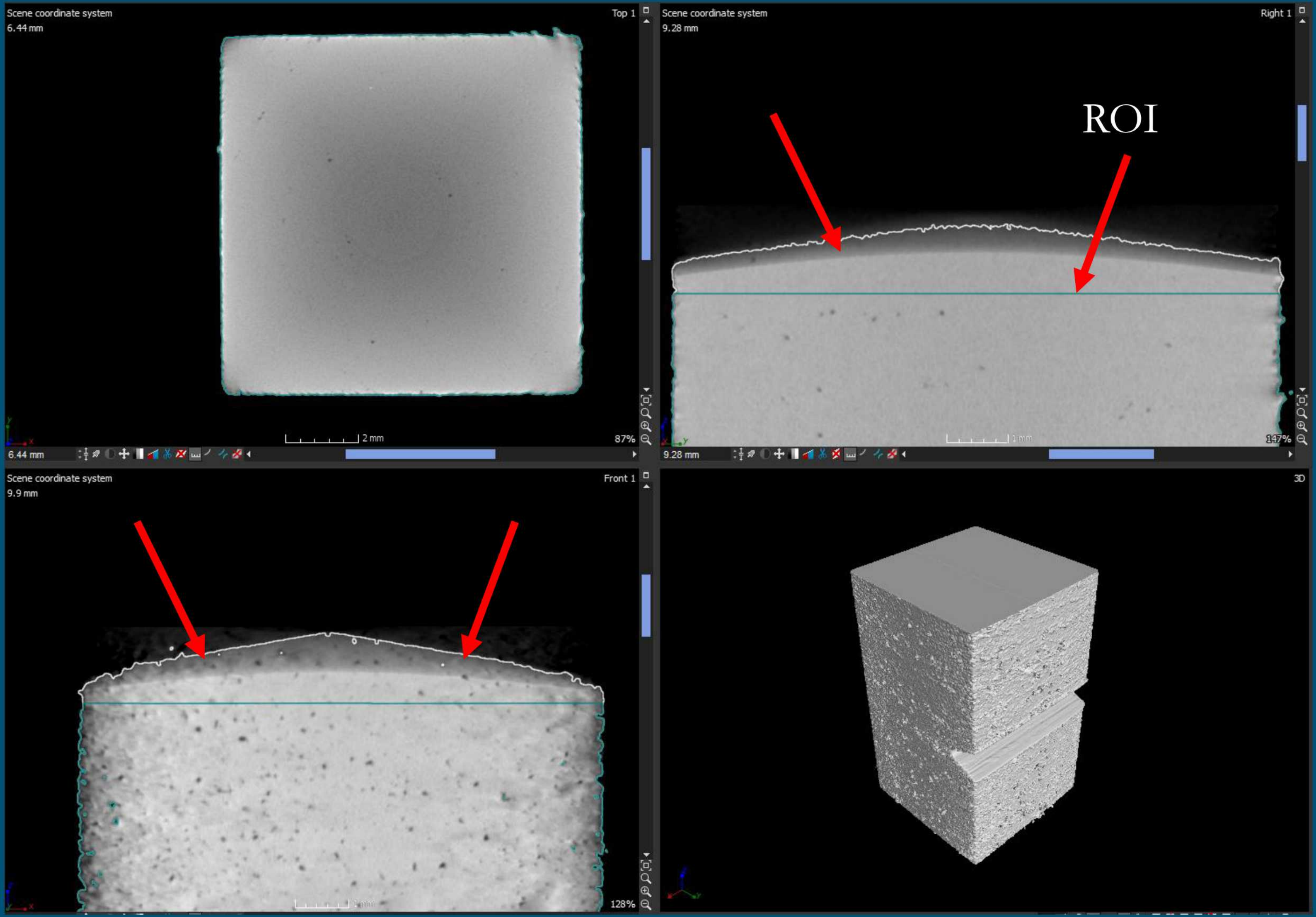
Surface Roughness:

- High surface roughness generally leads to more noise at the surface.
- Small concave surface roughness features are difficult to capture.
- These concave topographies can be mistaken for pores during porosity analysis.

Creation of Regions of Interest (ROI)

Segmented Volume
Vertical Build

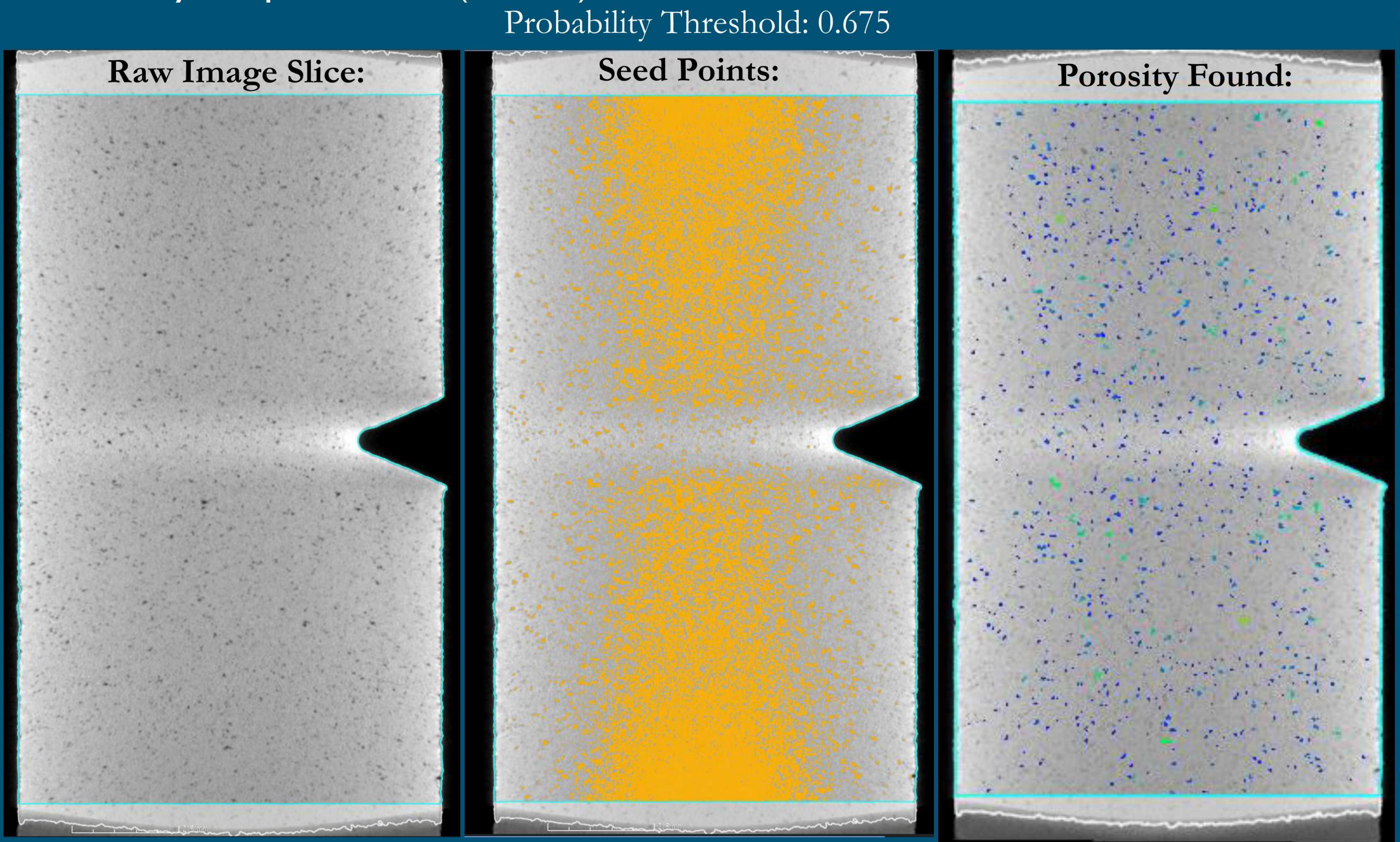




Results: Probability Dependence (1 of 2)

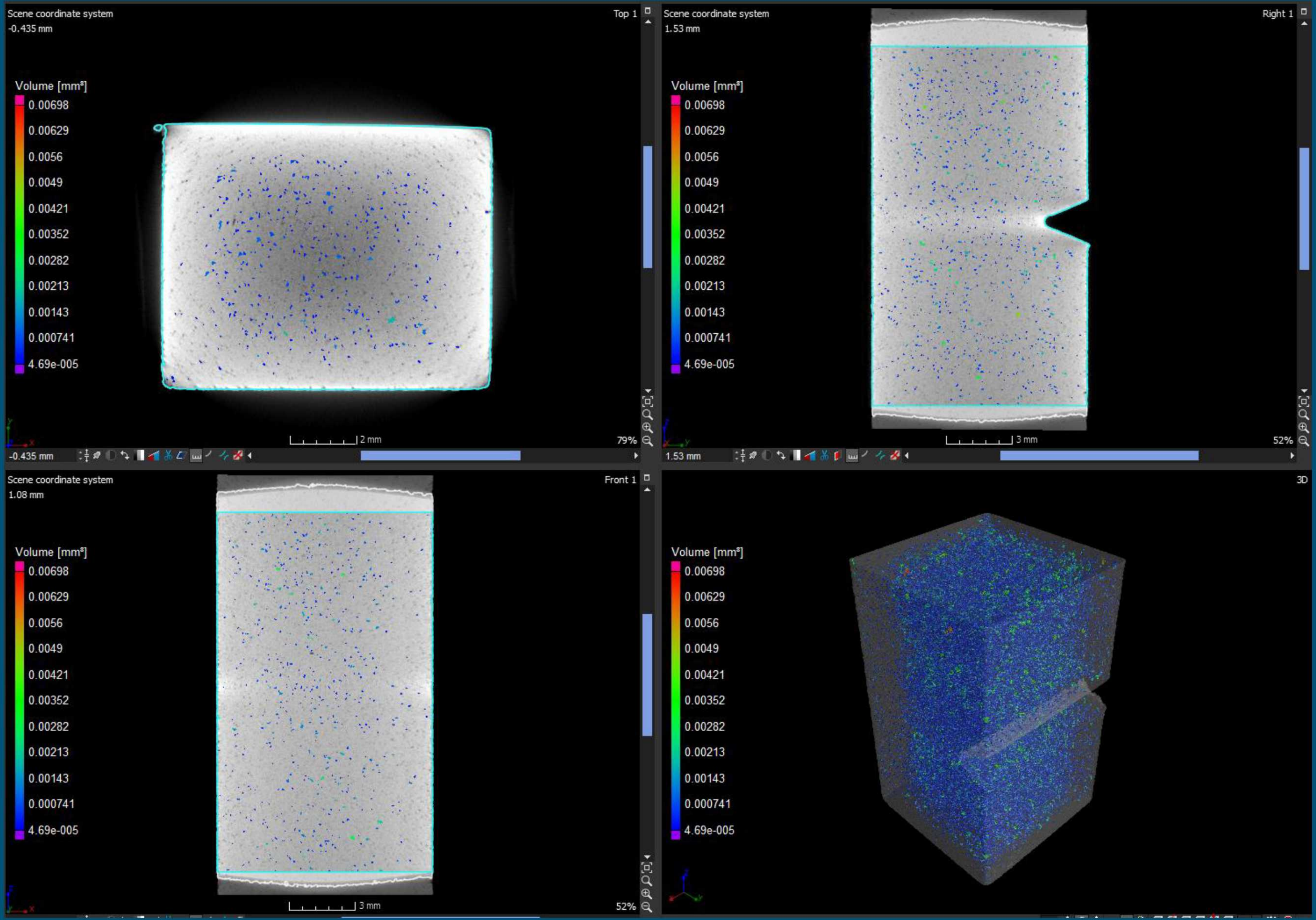
Low Global Energy Density (GED)

Vertical build



Results: Probability Dependence (2 of 2)

Probability Threshold: 0.675



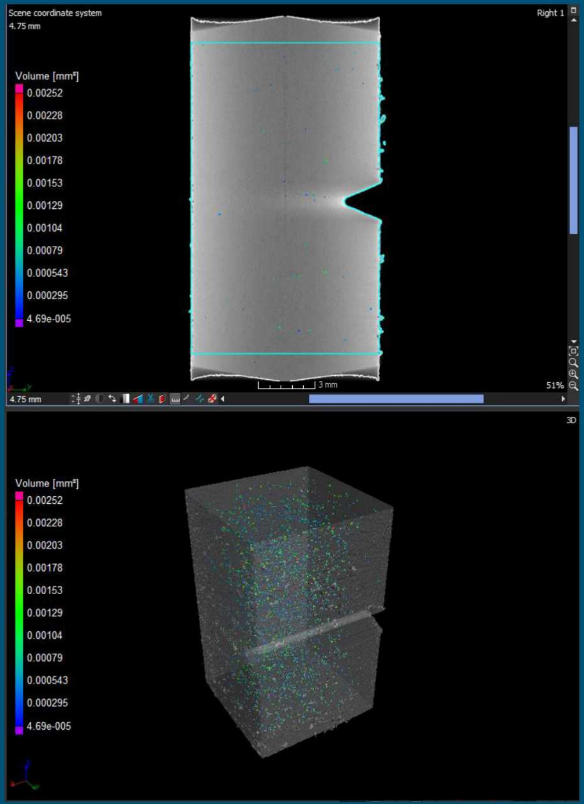
Low Global Energy Density

- Showed the most distinct porosity out of all of the samples
- Setting the probability threshold to 0.675 finds the porosity of interest. This observation is confirmed from a visual inspection of all the slice planes from the reconstructed CT data.
- Porosity near the surface is harder to identify due to the effects of beam hardening and surface concave topographies.

Results: Global Energy Density (GED) Vertical Build

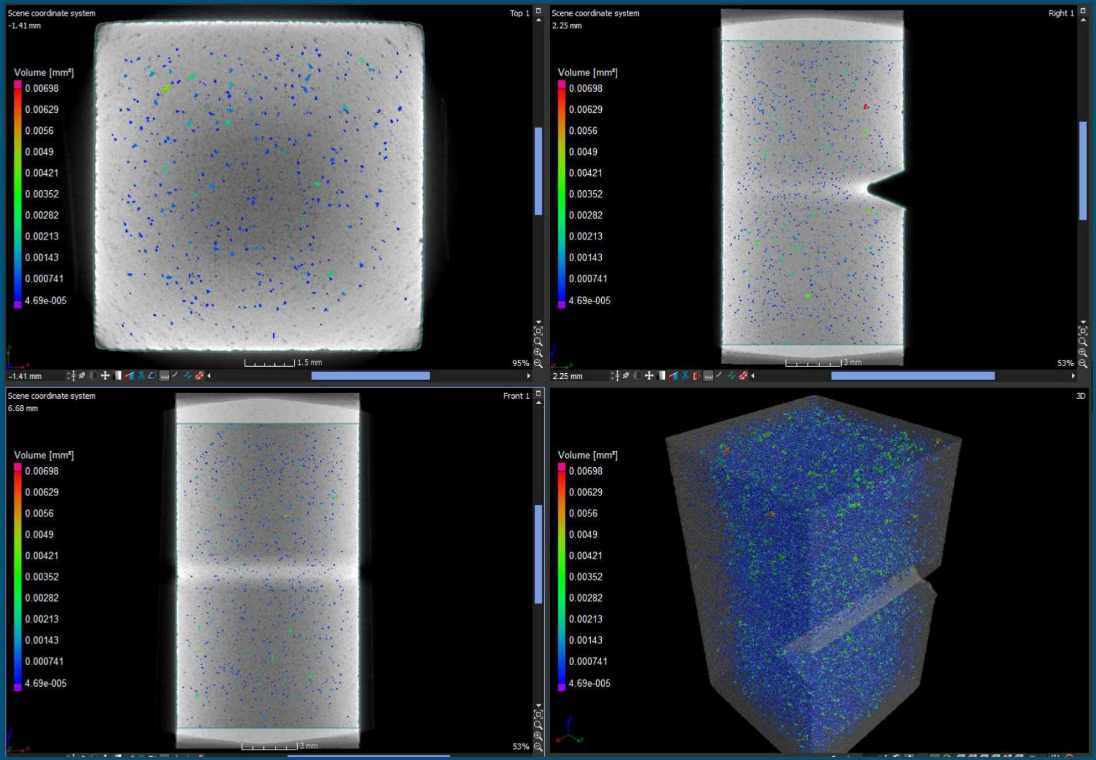
High GED

- Second largest individual pore volume
- Second largest number of pores
- Porosity in the exterior regions was harder to identify due to the effects of beam hardening



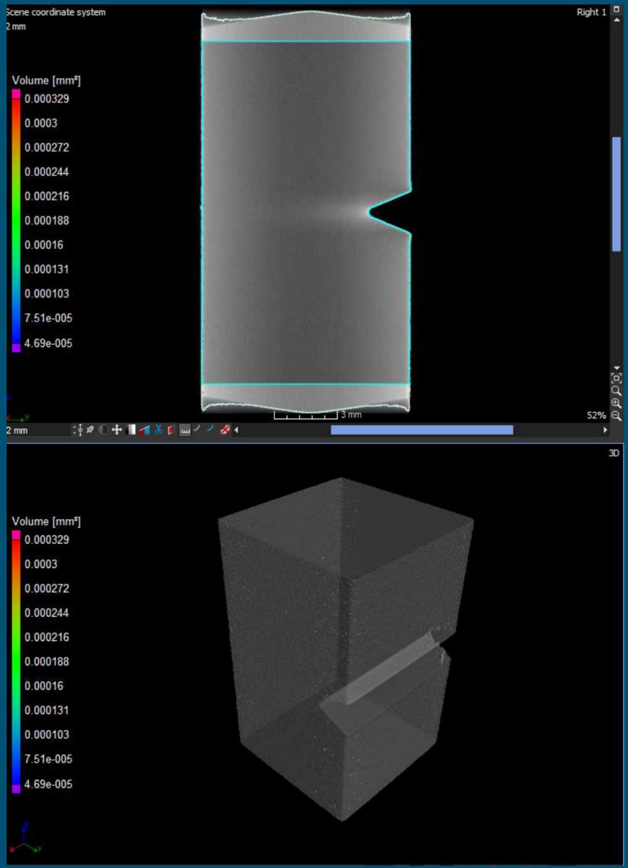
Low GED

- Largest individual pore volume
- Highest concentration of pores (out of the 3 samples)
- Porosity in the exterior regions was harder to identify due to the effects of beam hardening
- Large pores were distributed throughout the part volume



Nominal GED

- Smallest individual pore volume
- Almost no porosity found
- Distribution of pores is around the center of rotation and at the edges of the part
- Given that most of the volume has no porosity, pores identified near the surface are similarly causing outliers in the porosity percentage.



Results: Global Energy Density (GED) Horizontal Build

High GED

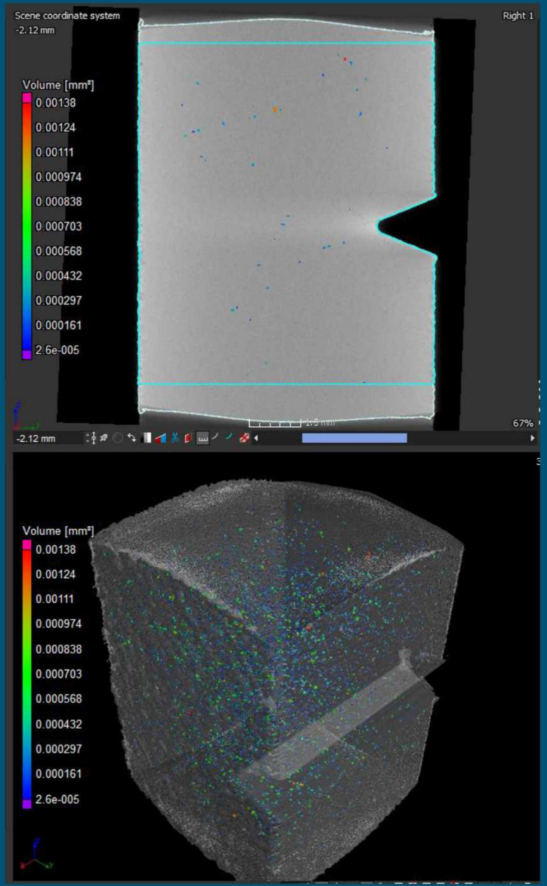
- Second largest individual pore volume
- Second largest number of pores
- Porosity in the exterior regions was harder to identify due to the effects of beam hardening

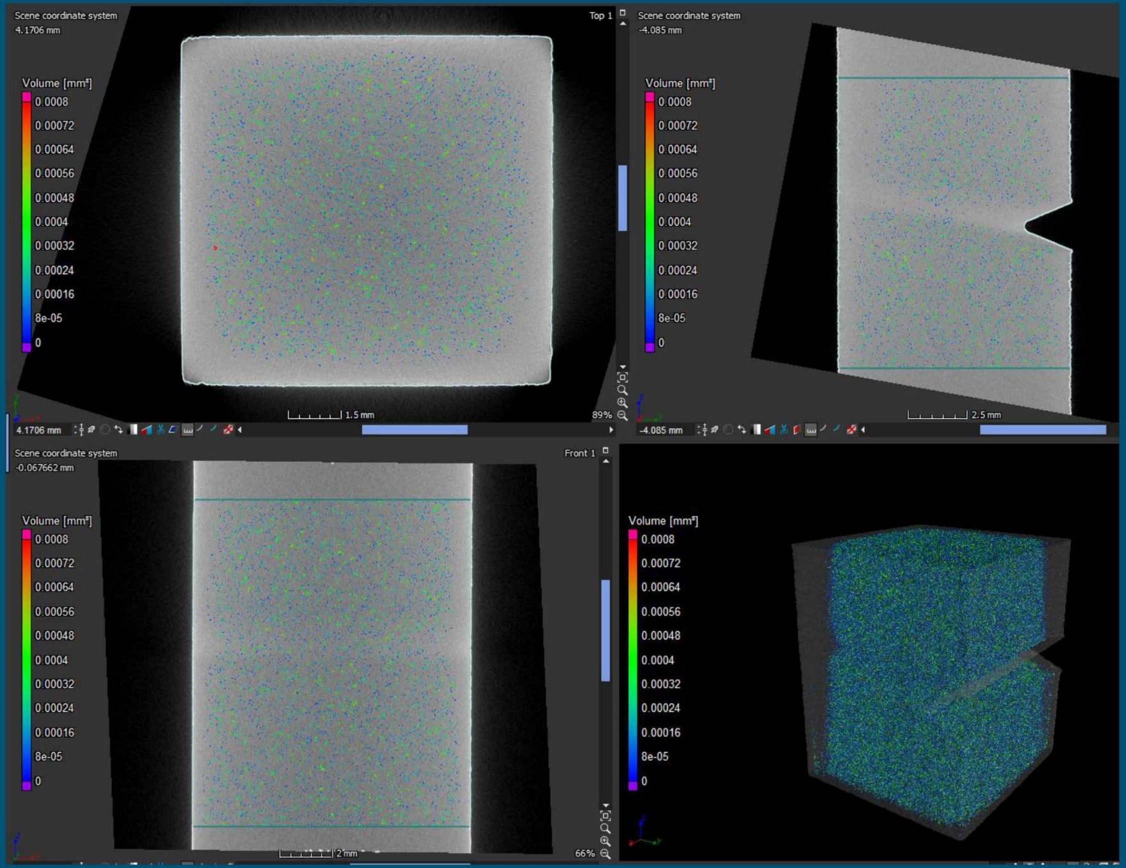
Low GED

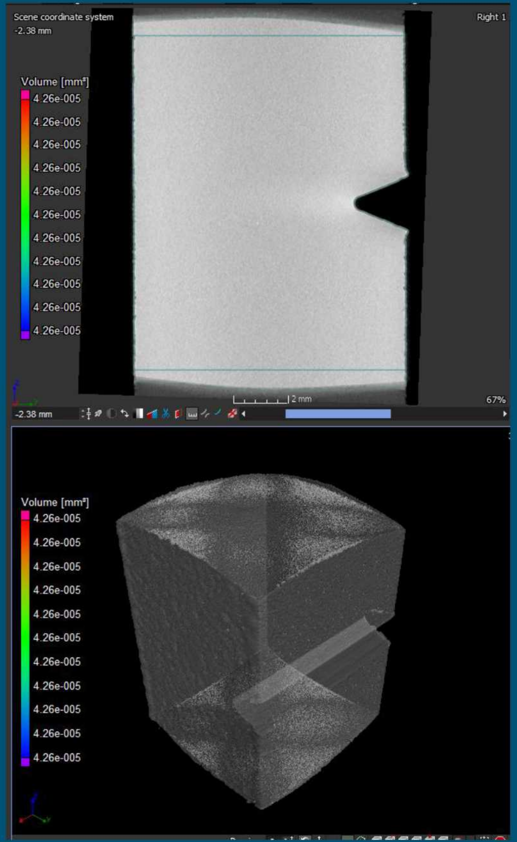
- Smaller pores and higher concentration of pores
- Porosity in the exterior regions was harder to identify due to the effects of beam hardening. Large pores were distributed more distributed throughout the part volume.
- CT center ring artifact produces some false positives

Nominal GED

- Smallest individual pore volume, almost no porosity found
- Distribution of pores is around the center of rotation and at the edges of the part
- Given that most of the volume has no porosity, pores identified near the surface are similarly causing outliers in the porosity percentage.





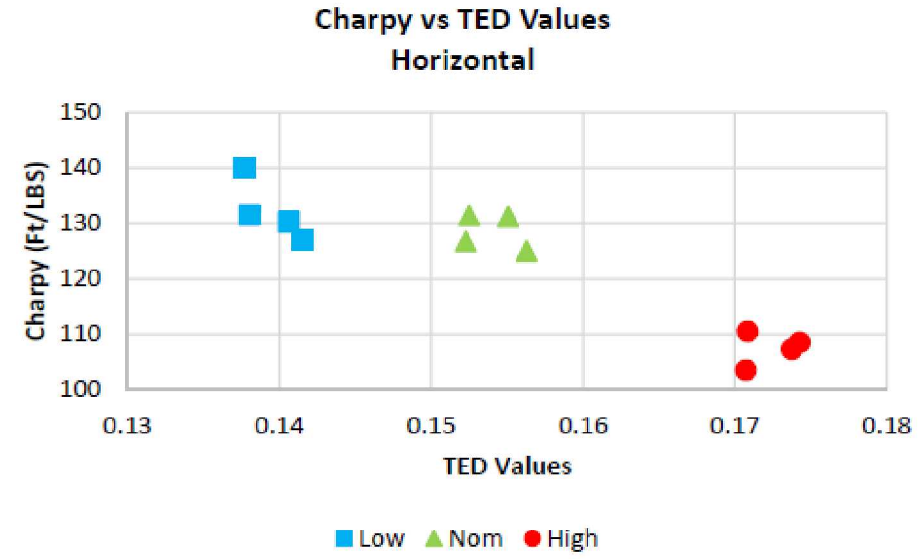


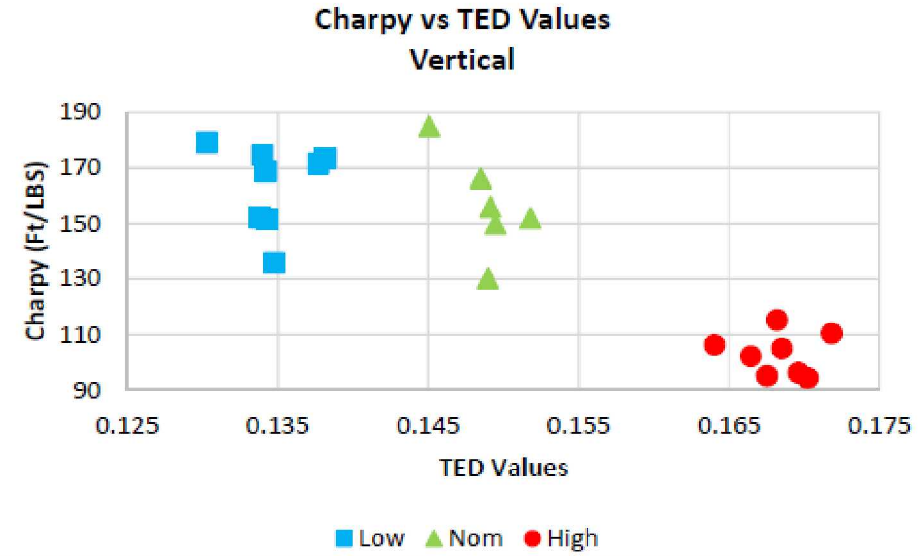
Charpy Impact Results

Charpy vs TED does not exhibit a trend when all specimens are plotted together, but when the data is separated into horizontal and vertical specimens, it is clear that both specimens have a plateau for low and nominal GED and a drop-off for the high GED Charpy values.

Density is related to a TED value. The plateau-drop-off behavior and Charpy results display a linear curve fit. These trends agree with expectations.

The separation from the horizontal and vertical builds are influenced by the grain orientation. Charpy impact toughness is significantly correlated to density. The density range for specimens is near ~ 98% with error of ± 0.1%.





Summary of Results (Software Volume Analysis)

VGEasyPore finds the least amount of porosity, but is significantly easier to use. Mild to negligible porosity increase along the direction of the array. This observation is clear in VG Easy Pore and somewhat apparent in VGDefX “Custom”

The general probability criterion from the VGDefX analysis finds the most porosity, but also computes the most false positive identification of pores. VGEasyPore is prone to assuming that the porosity found is closer to a sphere than that which is found by the ‘general’ and ‘custom’ probability criterion of VGDefX

The fractures are not always nucleating at specific sites or large voids regions. Both VGEasyPore and ‘custom’ probability criterion VGDefX tend to overestimate pore size. Additional source of error is incorrect joining of likely non-connecting pore regions and overgrowth of porosity from the seed points.

Summary of GED Produced Samples

Low GED creates low individual pore volume but highest number of pores with the region of interest (gage volume and Charpy ROI).

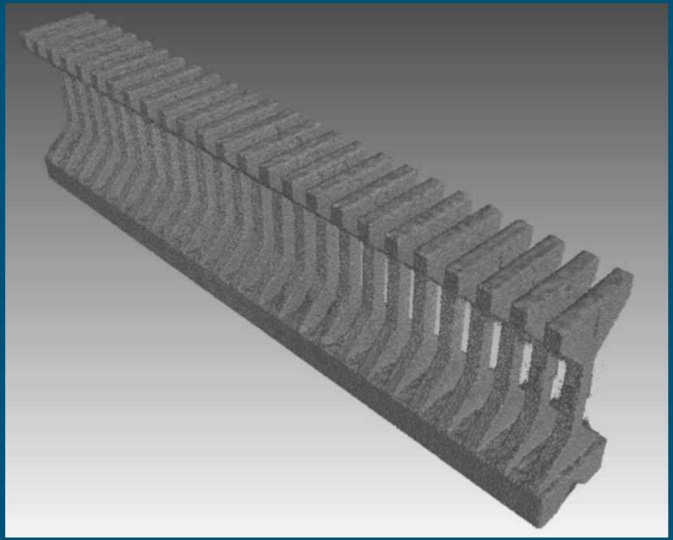
Nominal GED creates low individual pore volume and lowest number of pores within the region of interest (gage volume).

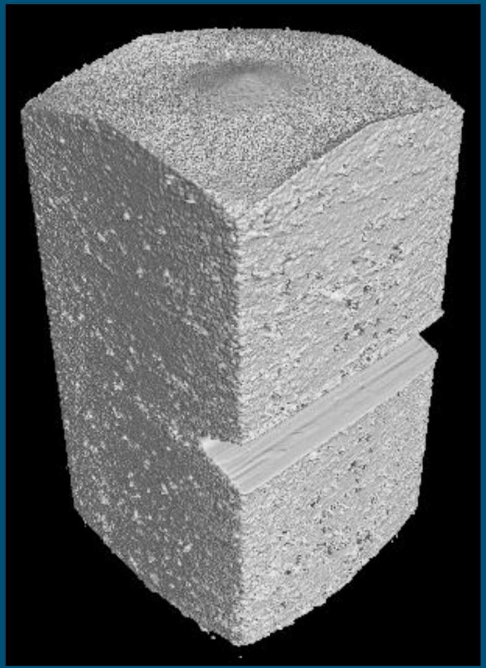
Nominal GED creates the smallest individual pore volumes and almost no pores within the region of interest (Charpy volume of interest).

High GED creates high individual pore volume and intermediate number of pores within the region of interest (gage volume).

High GED creates the second largest individual pore volume and the second largest number of pores. Porosity in the exterior regions was harder to identify due to the effects of beam hardening (Charpy volume of interest).

There does not appear to be any dependence of Charpy impact toughness with location on the build plate. TED values appear independent of sample location. Density values are also not location dependent.





Conclusions

Probability dependence, void diameter (compactness, volume, and sphericity) is calculated based on an assigned gray scale value. All detected gray scale values must be larger than the defined background voxels. This value is specified in the baseline materials definition menu within the software detection program. The local contrast threshold is specified within the program establishes the part's local contrast. If the voxel search area is brighter than the local contrast voxel level, a higher probability of detection is assigned to the voxel. A voxel-by-voxel grouping algorithm connects the voxel into a maximum likelihood for detection.

Filtering the results based on probability has a large effect on the total number of pores detected can be based on compactness volume and sphericity. Adjusting these variables help reduce the prevalence of long and thin pores that commonly result from noise in the scanned region of interest.

Additive Manufacturing process performance is spatial energy dependent and not a point property value. The manufacturability trade space is not apparent. The size, scale, feature and geometry will change the mechanical properties and the porosity distribution within the specimen. The processing engineer must document microstructure changes with respect to AM process settings. Dog bone tensile samples may be a quick experimental approach for process mapping and help determine the optimum setting of laser power and velocity.

When porosity forms a trail within several layers, the laser power is too high and does not allow proper evaporation of the gas from the liquid before the metal solidifies. Computed tomography has the ability to analyze spatial distribution of lack of fusion and porosity within a sample.

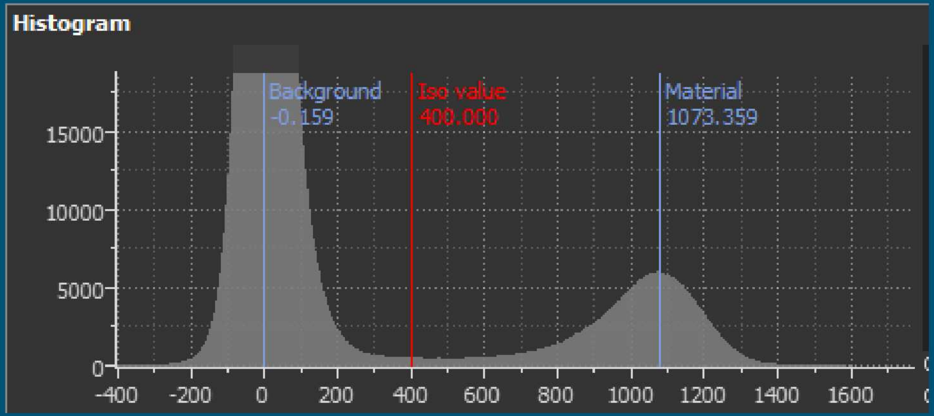
The structural cross sectional area was significantly lower in the dog bone tensile samples. This is due to surface roughness, surface crust and porosity within the samples. The unloading modulus is considerably less than 195 GPa. This indicates that approximately 30 percent of the cross sectional area does not contribute to the strength.

Backup

Evaluation Methodology: Segmentation

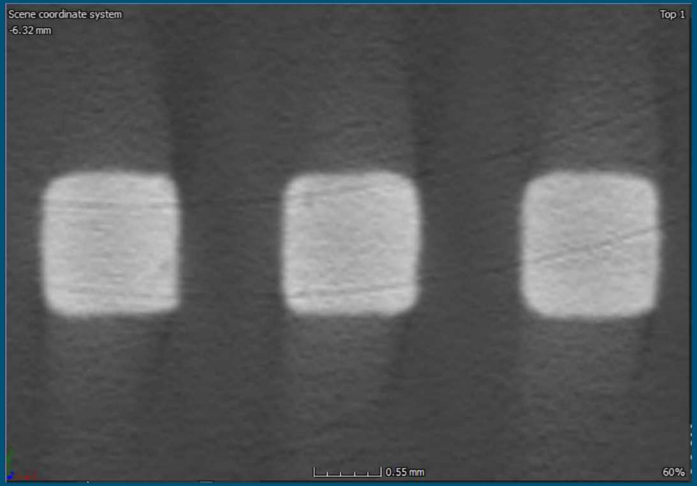
Refinement with Deformable Surface:

- Refine predefined surface with translation along surface normal to optimal location.
- Remove all voids and noise particles
- Search distance 0.1198 mm.

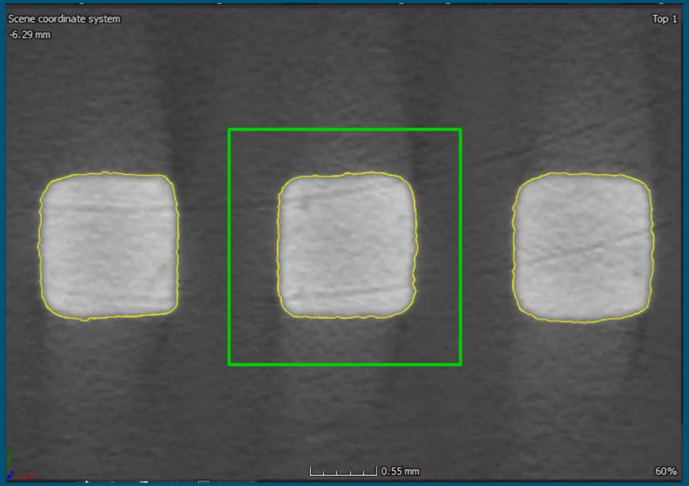


Global Thresholding with Advanced Deformable Surface:

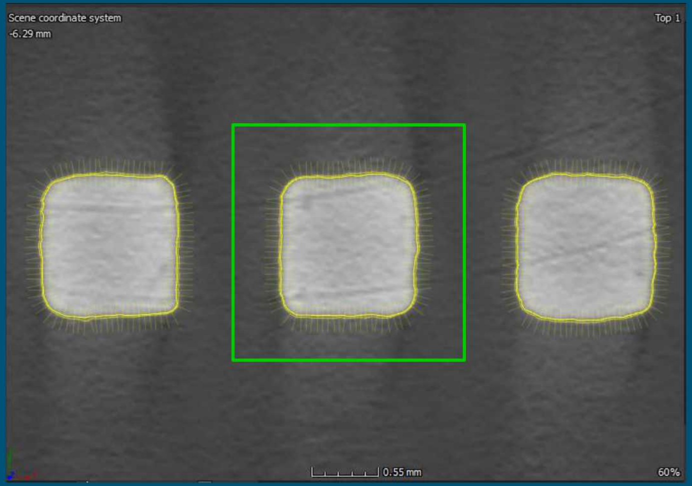
- Threshold Value: 400
- Material Value: 1073.359
- Background Value: -0.159



Raw intensity image



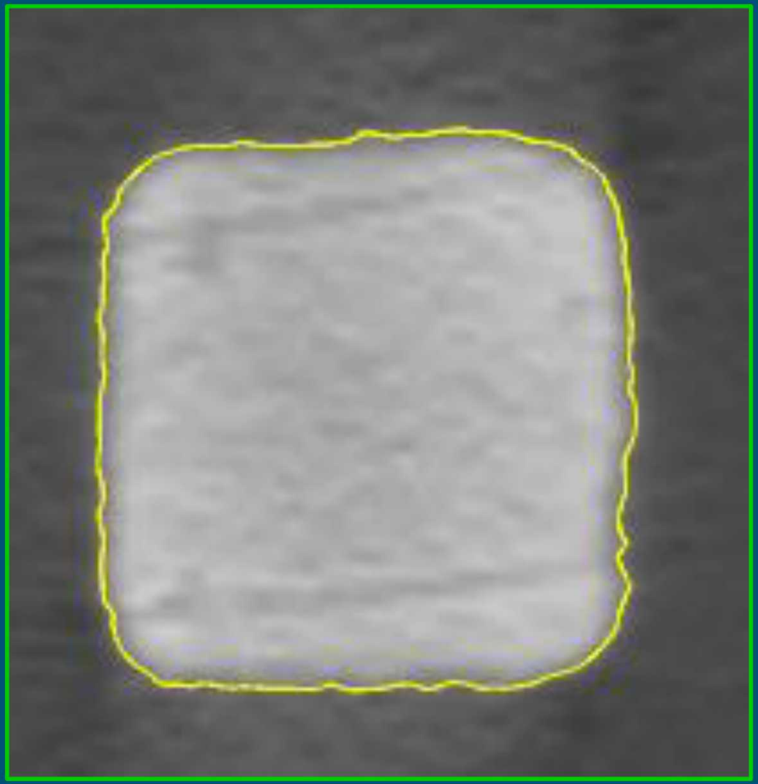
Global ISO-37 threshold



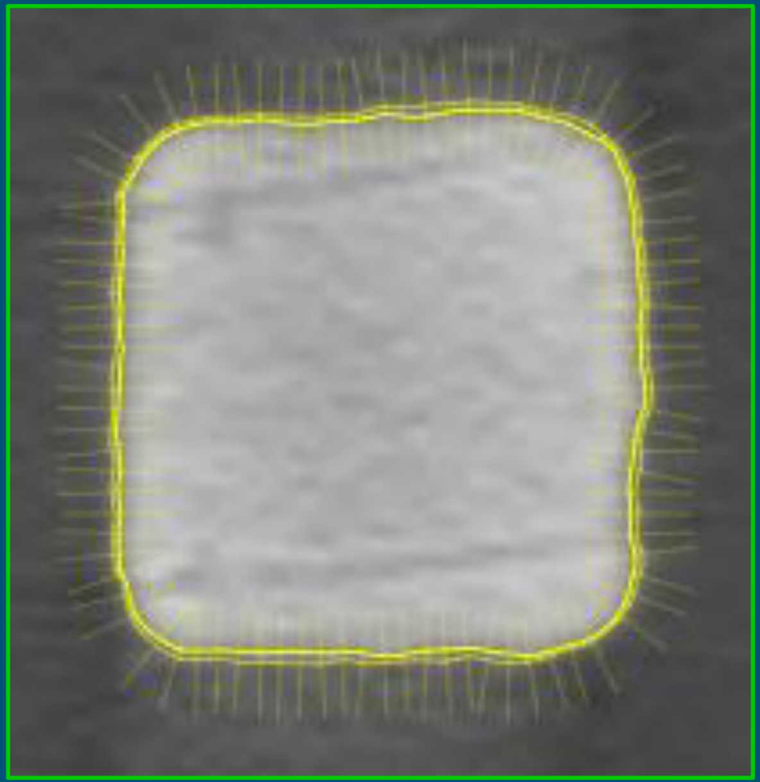
Advanced surface refinement with the removal of particles and voids

Evaluation Methodology: Segmentation

Reduction of surface gap



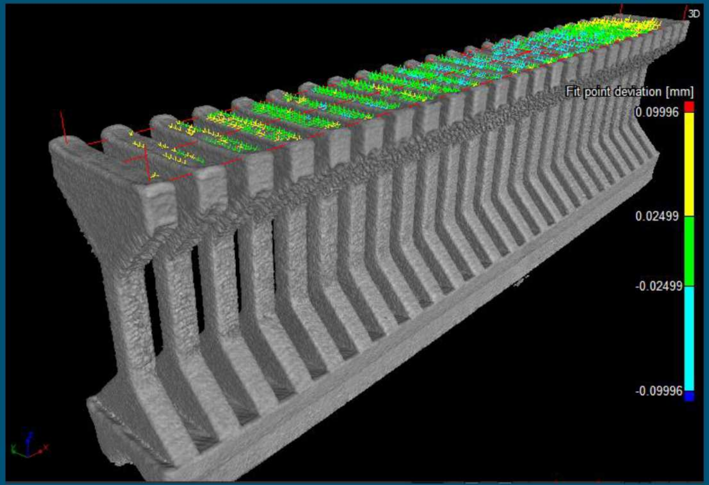
Global ISO-37 threshold



Advanced surface refinement with the removal of particles and voids

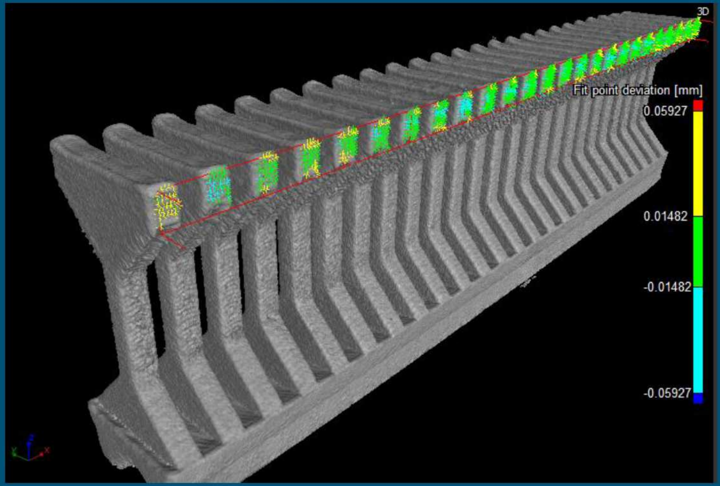
Evaluation Methodology: Registration

Specifying the top plane



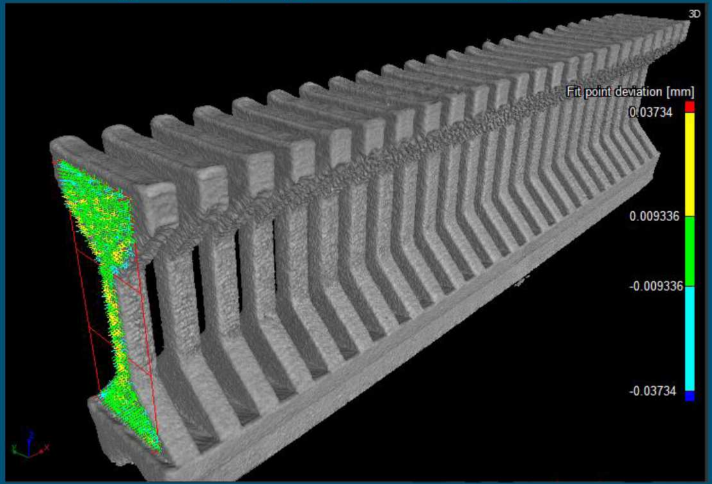
Intersect all 3-planes to create aligned coordinate system origin.

Specifying the side plane

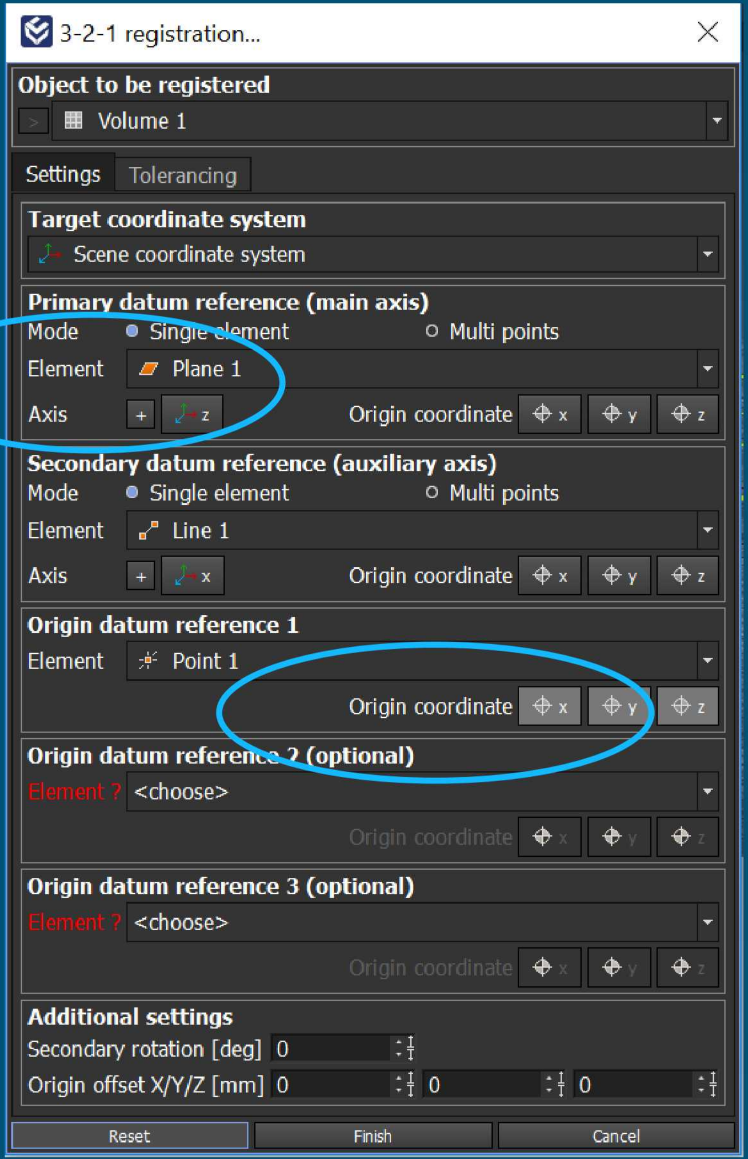


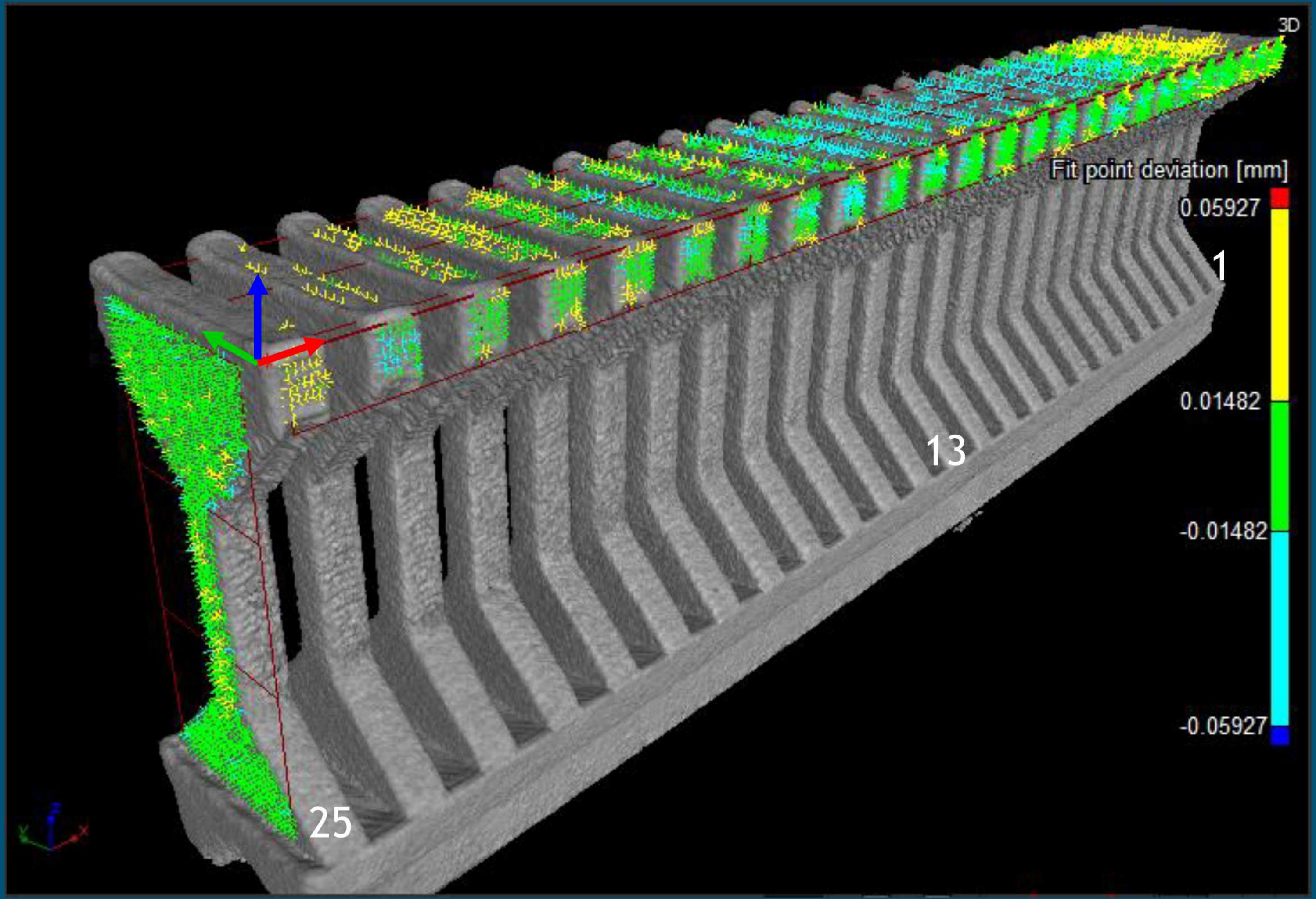
Intersect top and side to create x-axis.

Specifying the back plane



Evaluation Methodology: Registration





Notes:

There was not an apparent correlation with build direction and pore concentration or pore size. The presence of the center ring artifact does increase our uncertainty, but that increase is mostly confined to the local area/volume surrounding the rotational axis. Given the low amount of porosity identified in sample 26 horizontal build this effect is much more significant than in sample 27.

Upon further review, it would appear that specimen SN 26 has the same center of rotation/ring artifact problem as SN 27. Since the amount of porosity found in SN 26 is so much lower than SN 27, the consequences of this artifact are much more apparent in the 3D view of SN 26. Specimen SN27 had some semi-significant effects of a center of rotation/ring artifact That is causing some concentric porosity behavior.