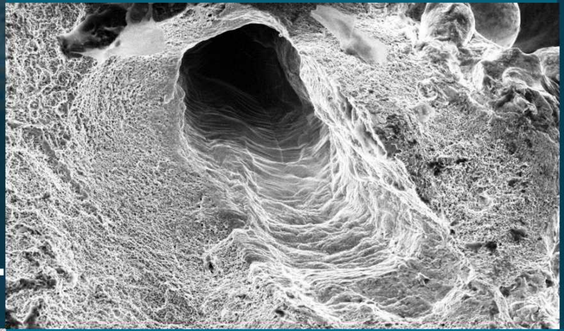
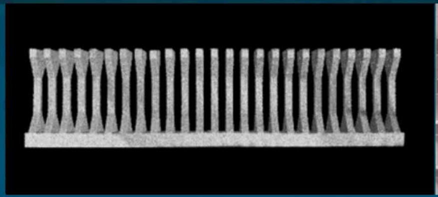
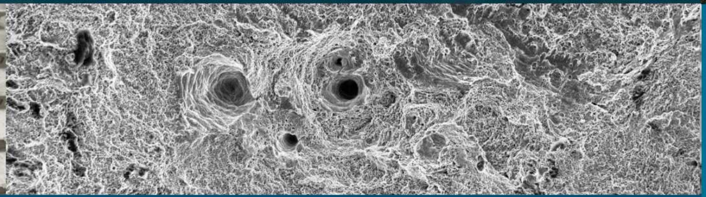
SAND2019-9789C

EFFECTS OF SPATIAL ENERGY DISTRIBUTION ON DEFECTS AND FRACTURE OF LPBF 316L STAINLESS STEEL







PRESENTED BY

Elliott Jost—*Solid Freeform Fabrication 2019—Austin, TX*

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Additive Manufacturing (AM)

Advantages of AM:

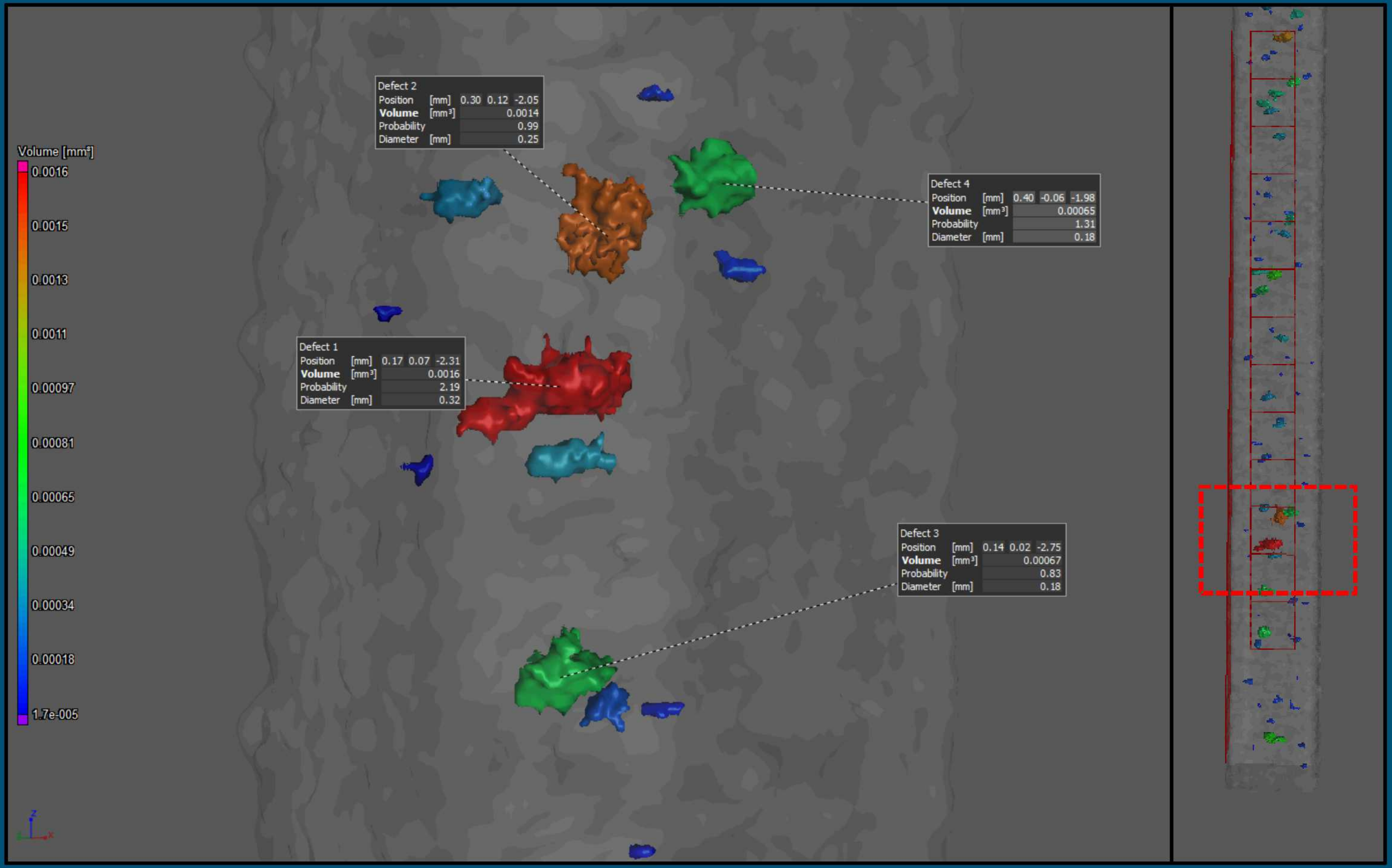
- Low cost-to-complexity ratio
- Low cost for small batches
- Ability to create complex geometries not possible with traditional methods

Challenges in AM:

- Optimal processing conditions
- Surface roughness & heterogeneities
- Internal defects—focus of this study
- **Qualification**
  - The determination of part integrity

Qualification methods include:

- In-situ melt pool monitoring
- Post-build Computed Tomography



The goal of this study is to understand the ***defect-property relationship*** in AM 316L SS to establish qualification specifications for AM parts.

Literature Review

In-situ Qualification:

- Craeghs et al. [7] used optical sensors to implement feedback control for surface roughness improvement.
- Spears and Gold [8] identified over 50 different process parameters that influence final part quality.
  - Highlights difficulty of the problem.

Computed Tomography (CT) Qualification

- Kim et al. [10] developed 3D image processing techniques for improved CT inspection reliability.
- Thompson et al. [12] discussed CT inspection for measurements of pore morphology, location, distribution.

Defect-Performance Relationship

- Gong et al. [17] found that low-energy input was more detrimental to performance than high-energy input (Ti64).
- Madison et al. [18] found little correlation between defect volume or number of defects and properties (304L SS)
- Carlton et al. [19] found voids acting as crack initiation sites (316L SS).

Study Introduction

Three build plates made at different Global Energy Density (GED) settings:

$$GED = \frac{P}{H*S}$$

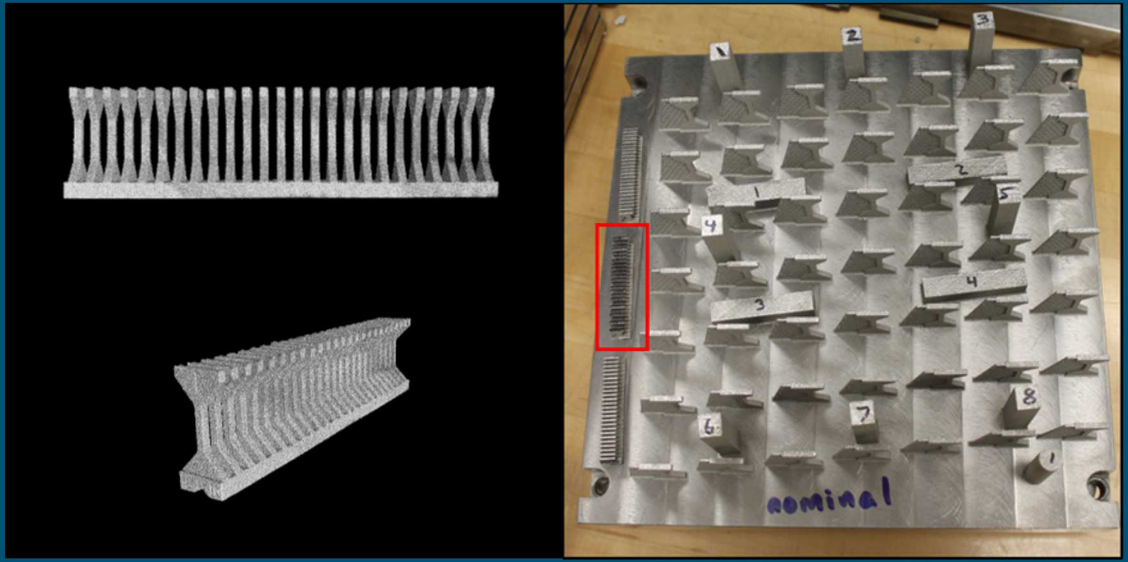
Where P is laser power, H is hatch spacing, and S is laser speed

Tensile specimen arrays with 25 dogbones were mechanically tested and relevant properties were calculated.

Correlations between SEM pore metrics and mechanical properties were made.

Printing Details:

- Sample Material: Stainless Steel 316L
- Produced on: EOS M 290
- Post Processing: None
- Build Parameters: Particle size 30 - 60 um Stainless Steel 316 -L, 400W IPG Photonics Laser.



	P (W)	H (mm)	S (mm/s)	GED (J/mm^2)
High GED	*220*	0.09	1083	**2.26**
Nom GED	*195*	0.09	1083	**2.00**
Low GED	*170*	0.09	1083	**1.74**

Inspection Methods: CT

All arrays were inspected using a Nikon M2 225/450kV CT system.

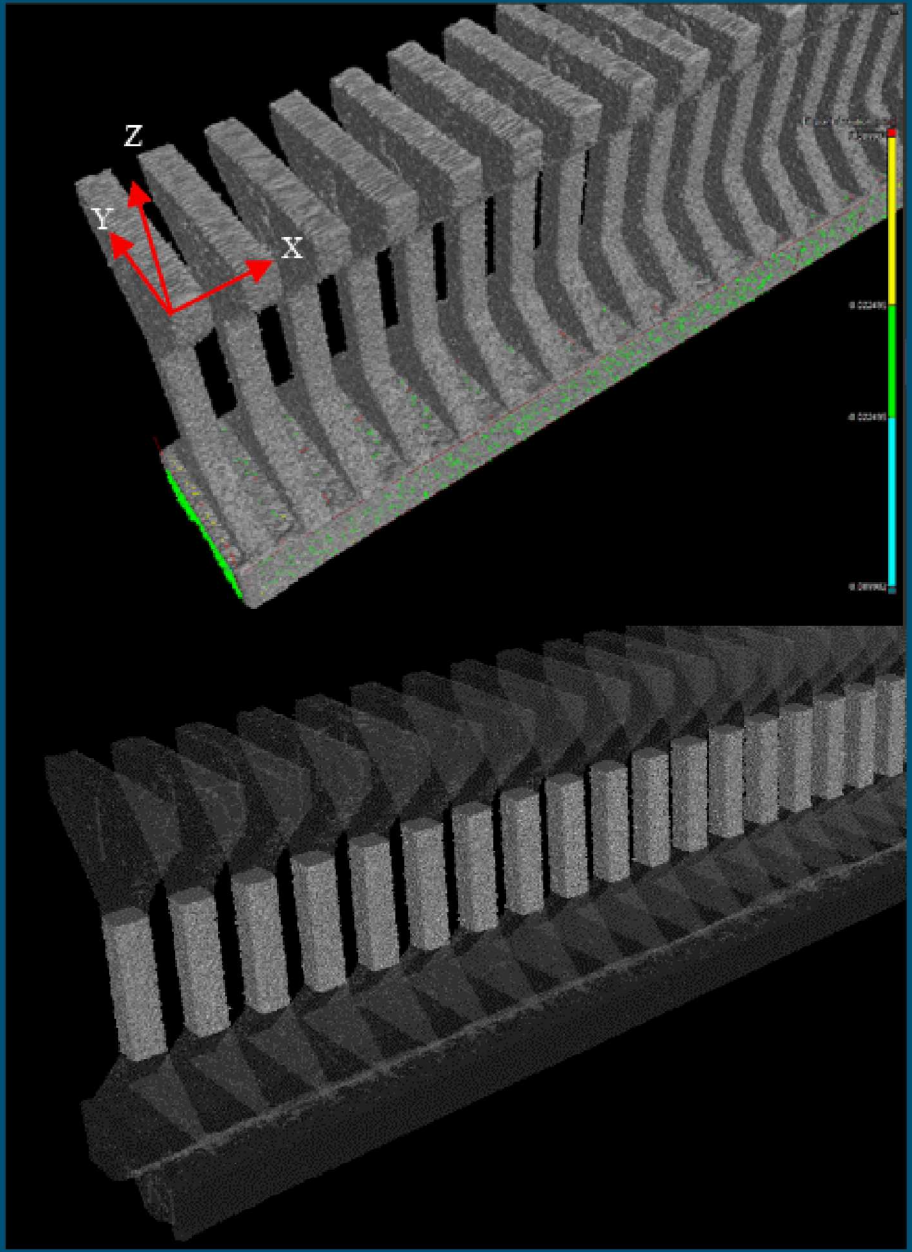
Parameter	Value
Num. of Projections	2294
Voltage	440 kV
Resolution	10 µm/voxel

Samples analyzed using Volume Graphics 3.2.

Porosity distributions were found to be spatially uniform in the z-direction.

Pore criteria:

Probability Threshold	Effective Pore Diameter [mm]	Compactness	Sphericity
>0.85	0.0625-1.00	0.08-1.00	0.13-0.65



Methods: Tensile Testing

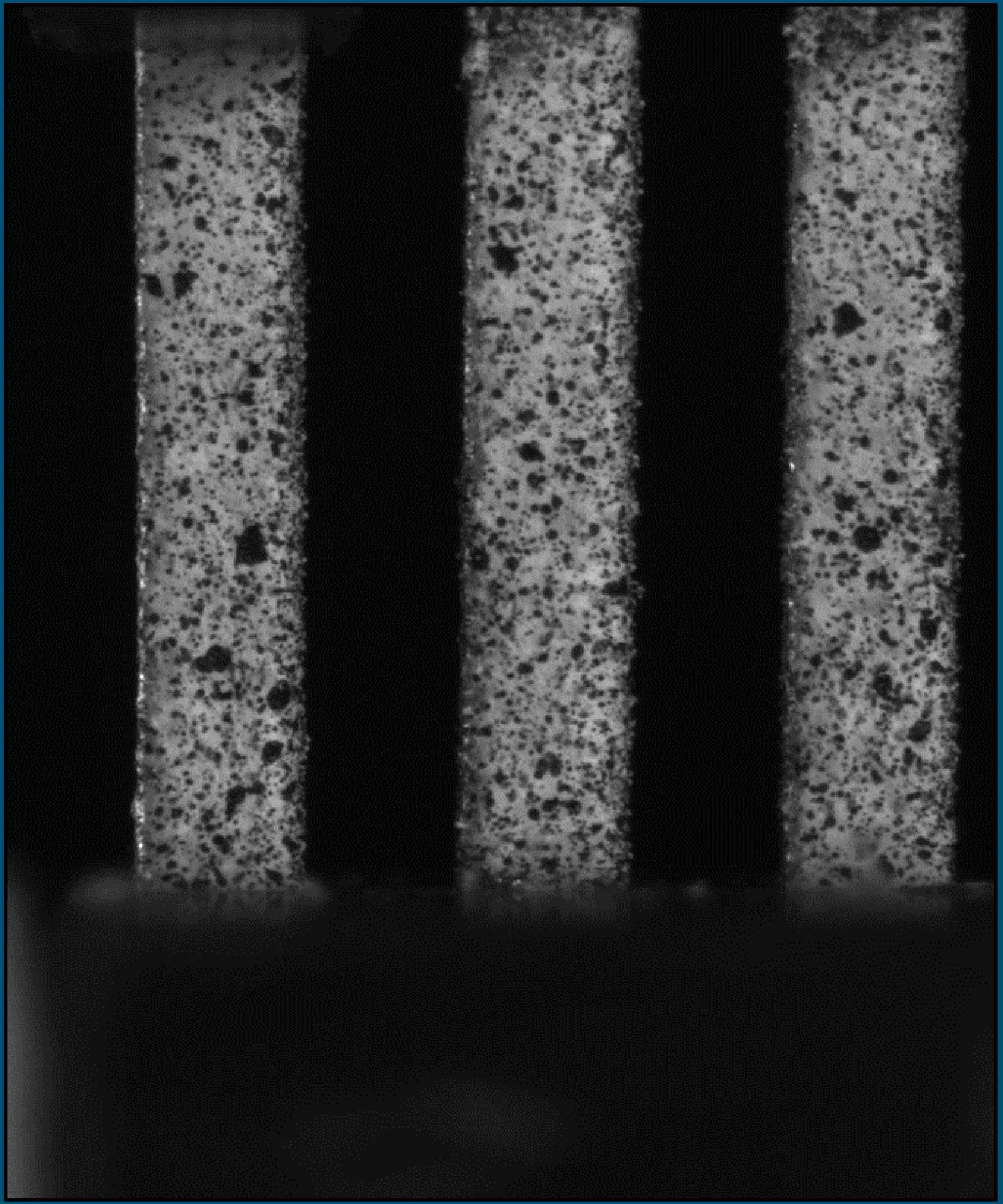
High-throughput mechanical testing was performed using an MTS load frame and a custom mounting stage for sample movement.

Stage capable of testing 50-100 samples/hour.

VIC-Gauge was employed for real-time DIC strain tracking.

Properties were extracted from the auto-generated stress-strain curves:

- UTS
- Elongation to failure
- Yield Strength



Inspection Methods: SEM

SEM images of bottoms of samples were analyzed manually using ImageJ.

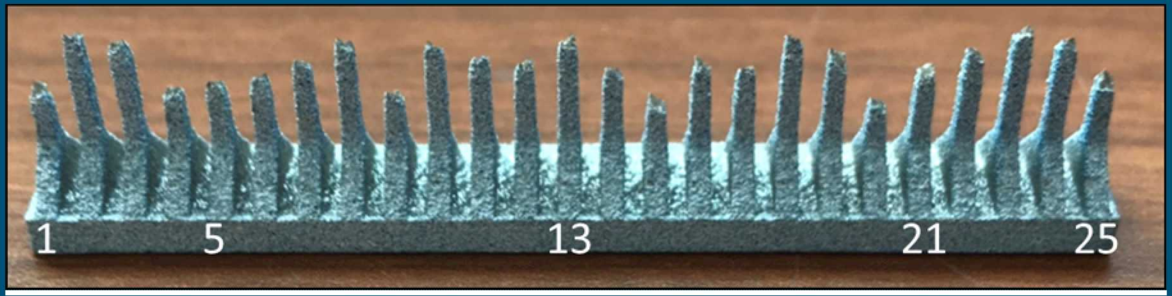
Pores were identified (freeform shape drawn around)

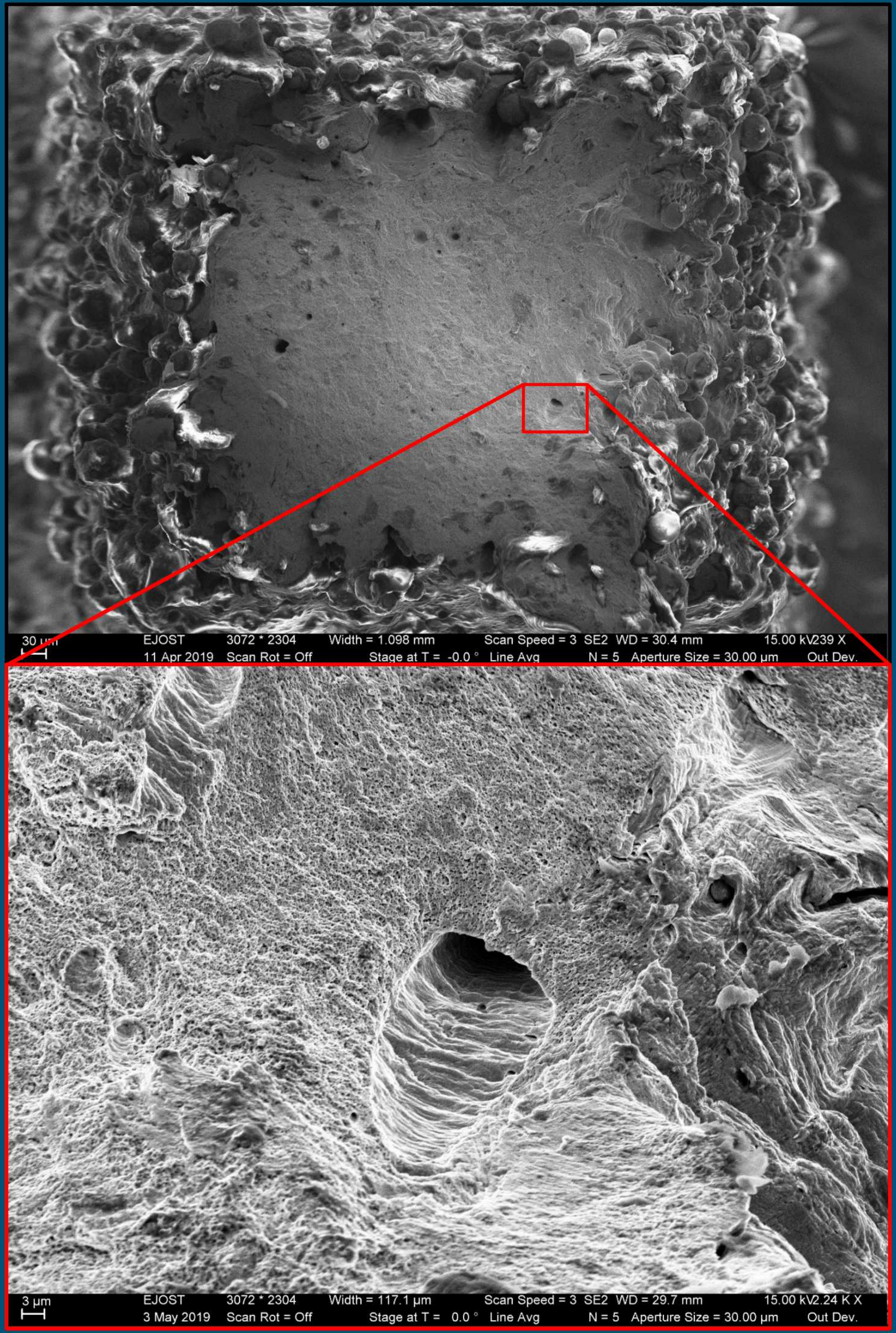
ImageJ calculated metrics such as: area, diameter, centroid, bounding box, and more

- Derivative metrics calculated from ImageJ results

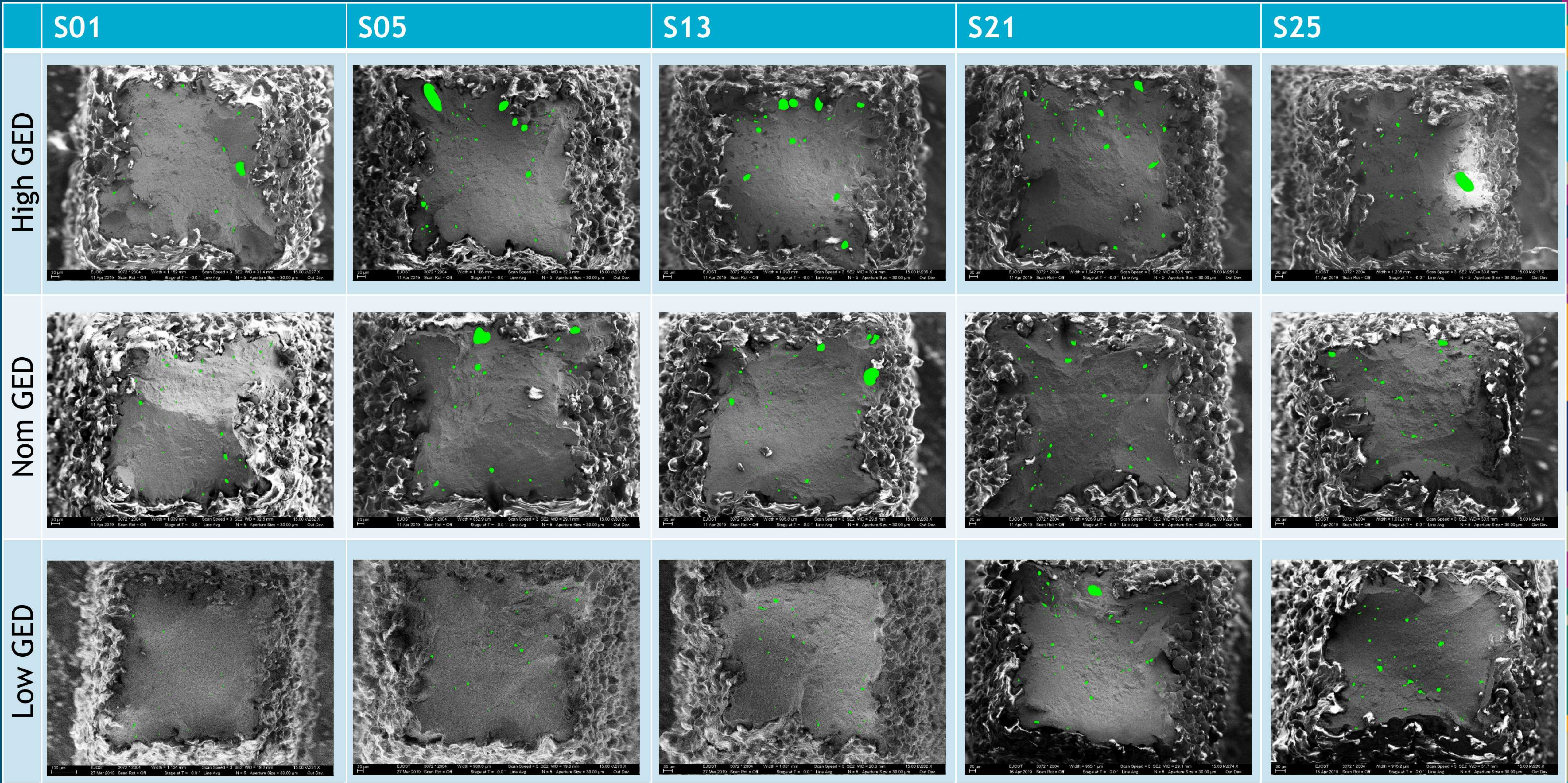
Samples 1, 5, 13, 21, and 25 were imaged from each GED set

- 647 pores across 15 samples identified and analyzed





Results: Porosity Overview

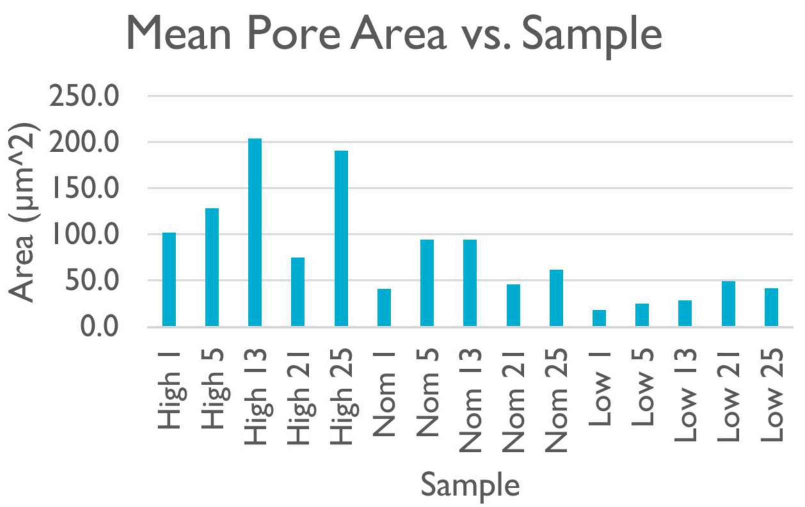


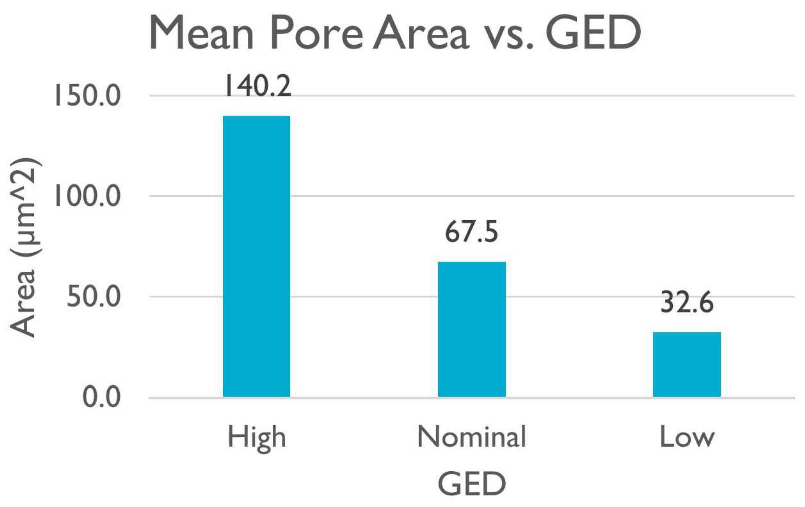
Results: Pore Area vs. GED

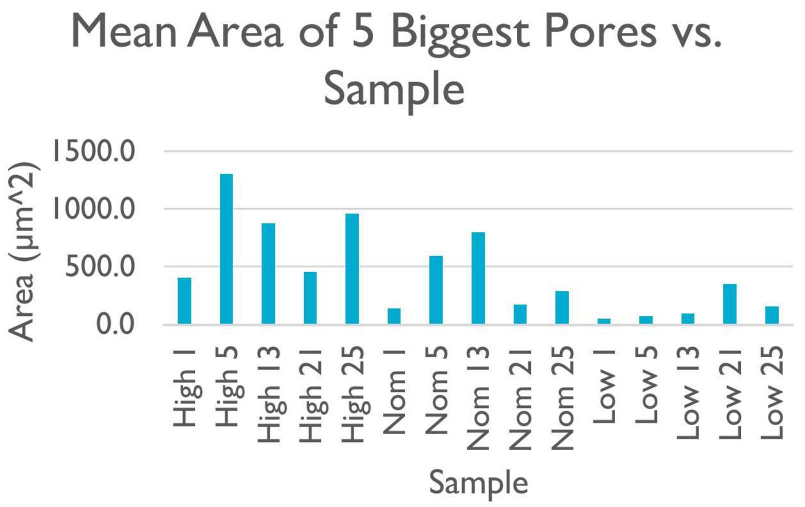
Positive correlation between GED and pore area.

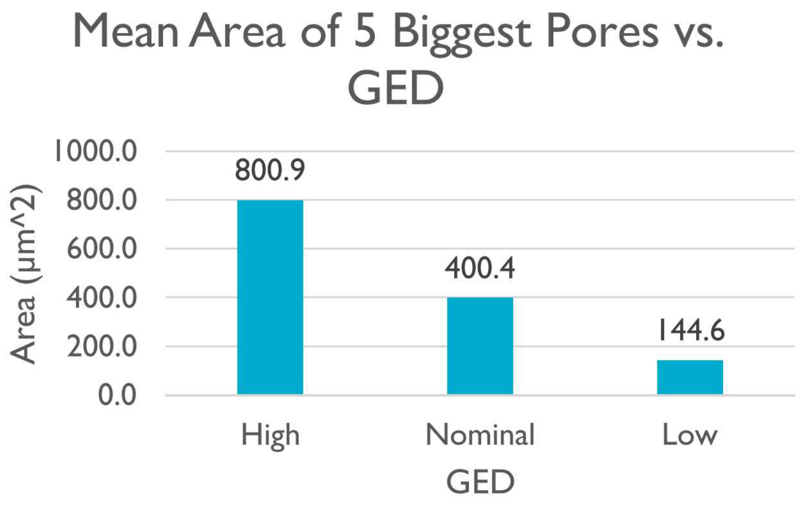
Trend exists even when considering the 5 largest pores on each fracture surface

5 largest pores are being investigated to determine whether thresholds can be set for qualification.





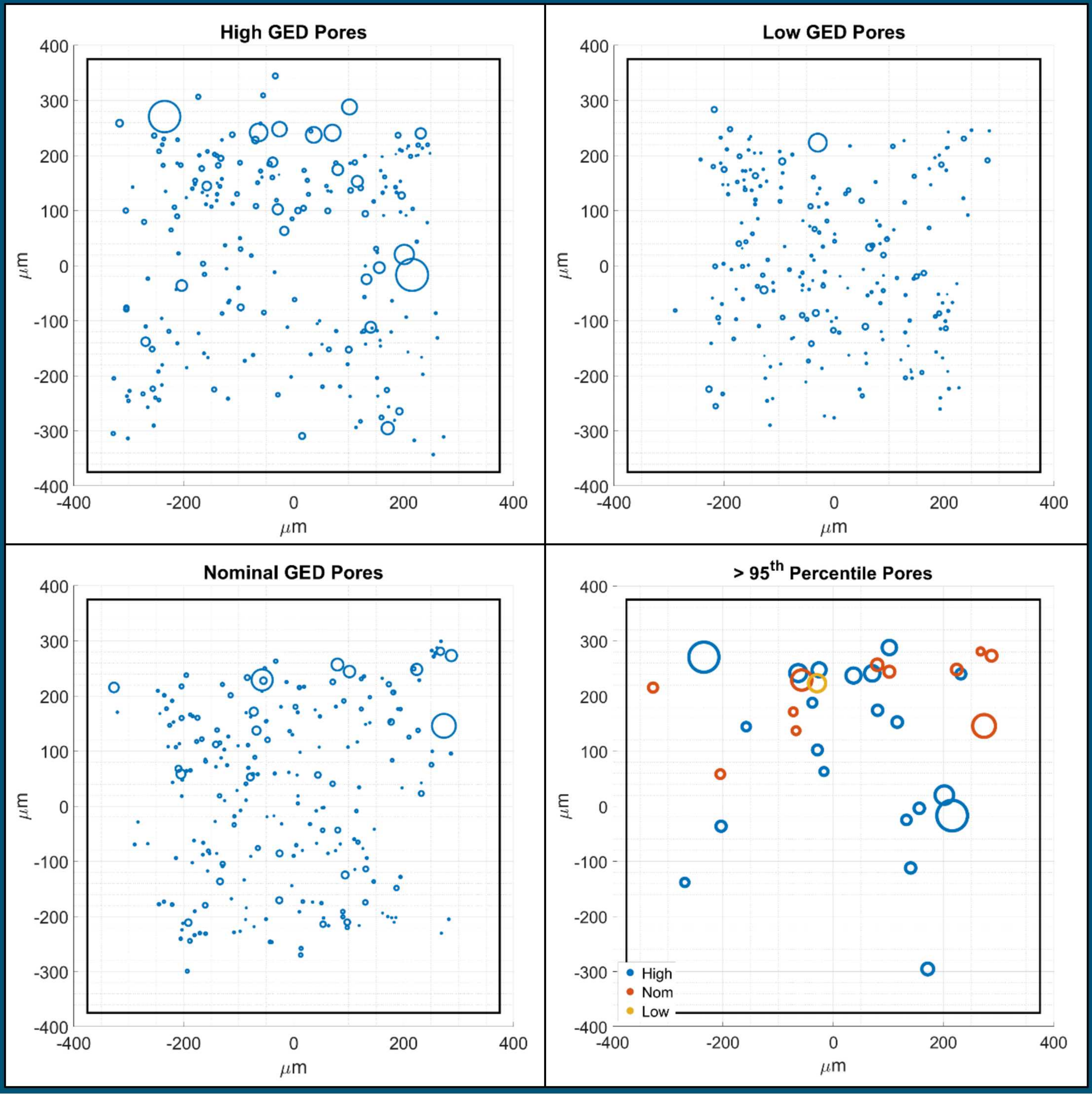




Pore Location vs. GED

Plots show pore location with markers scaled to *relative* area of pore (not scaled to actual pore size)

Largest Pores tend to be on High GED samples and near the edge of samples.



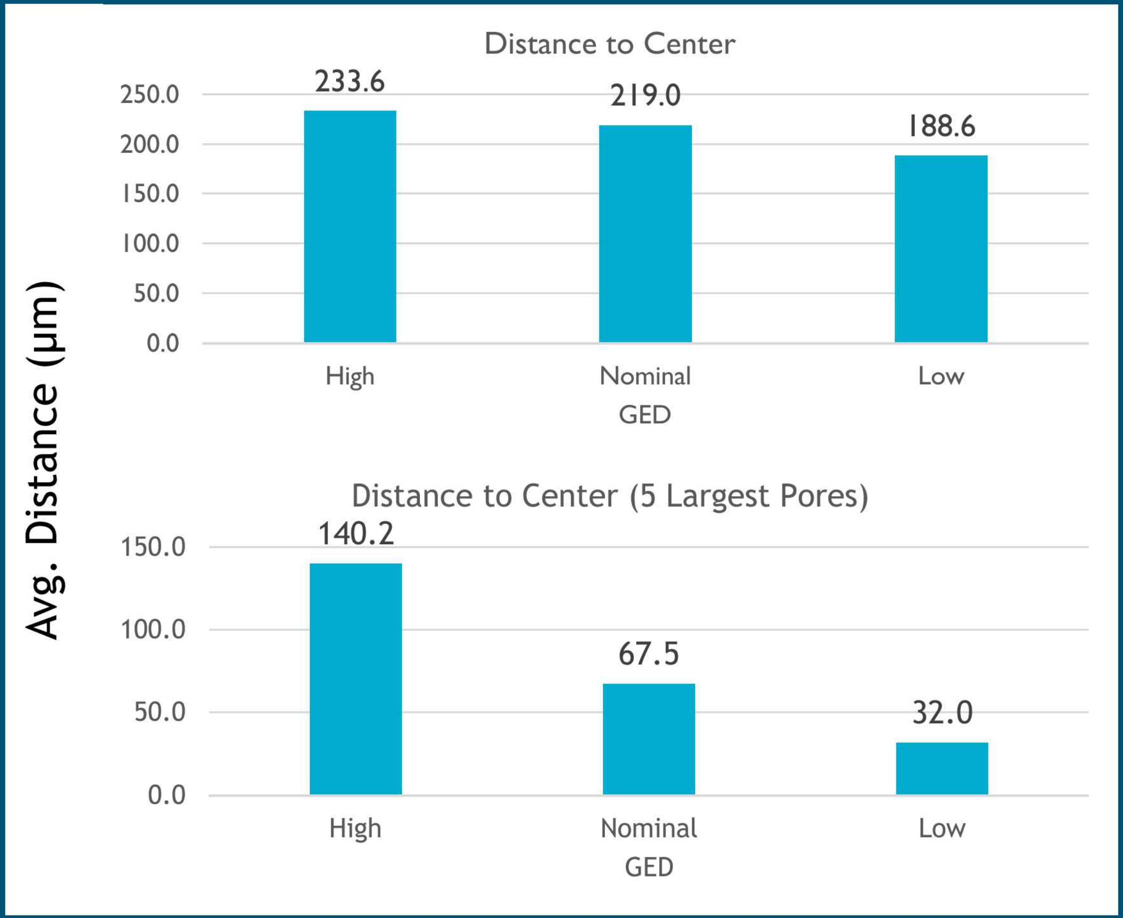
Porosity Cause

Largest pores are most likely **keyhole** porosity due to high energy input.

- Keyhole porosity caused by energy input being too high

Laser reversing direction causes high energy input at edges of sample.

Keyhole porosity linked to location of largest pores



Mechanical Properties vs. GED

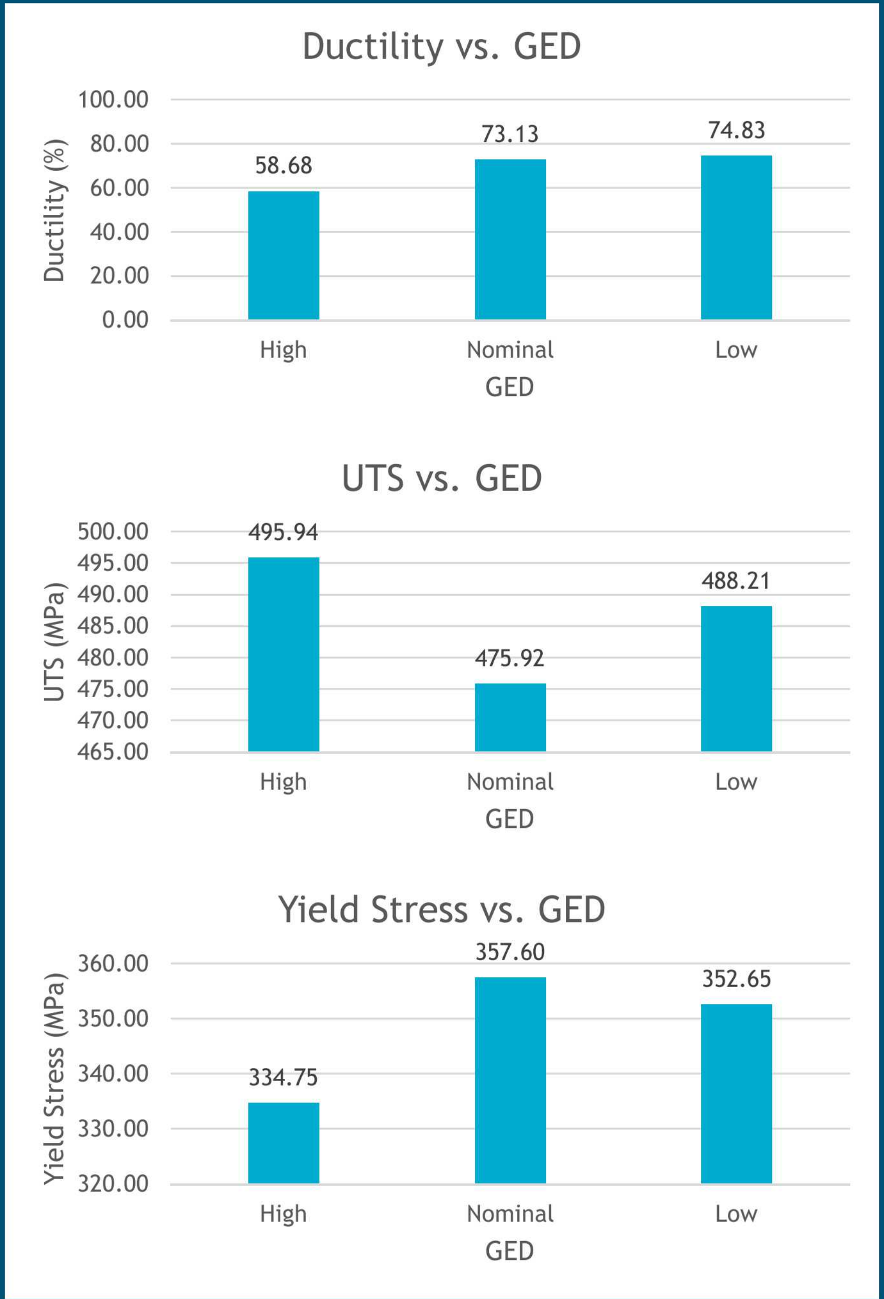
Ductility decreases up to an average of 25% due to non-optimal GED input (High GED).

UTS increases (~4%) with non-optimal GED input.

Yield Strength decreases up to an average of 7% with non-optimal GED input.

JE3

General trends are observed between mechanical properties and GED.



Slide 12

JE3 Unsure about saying this.

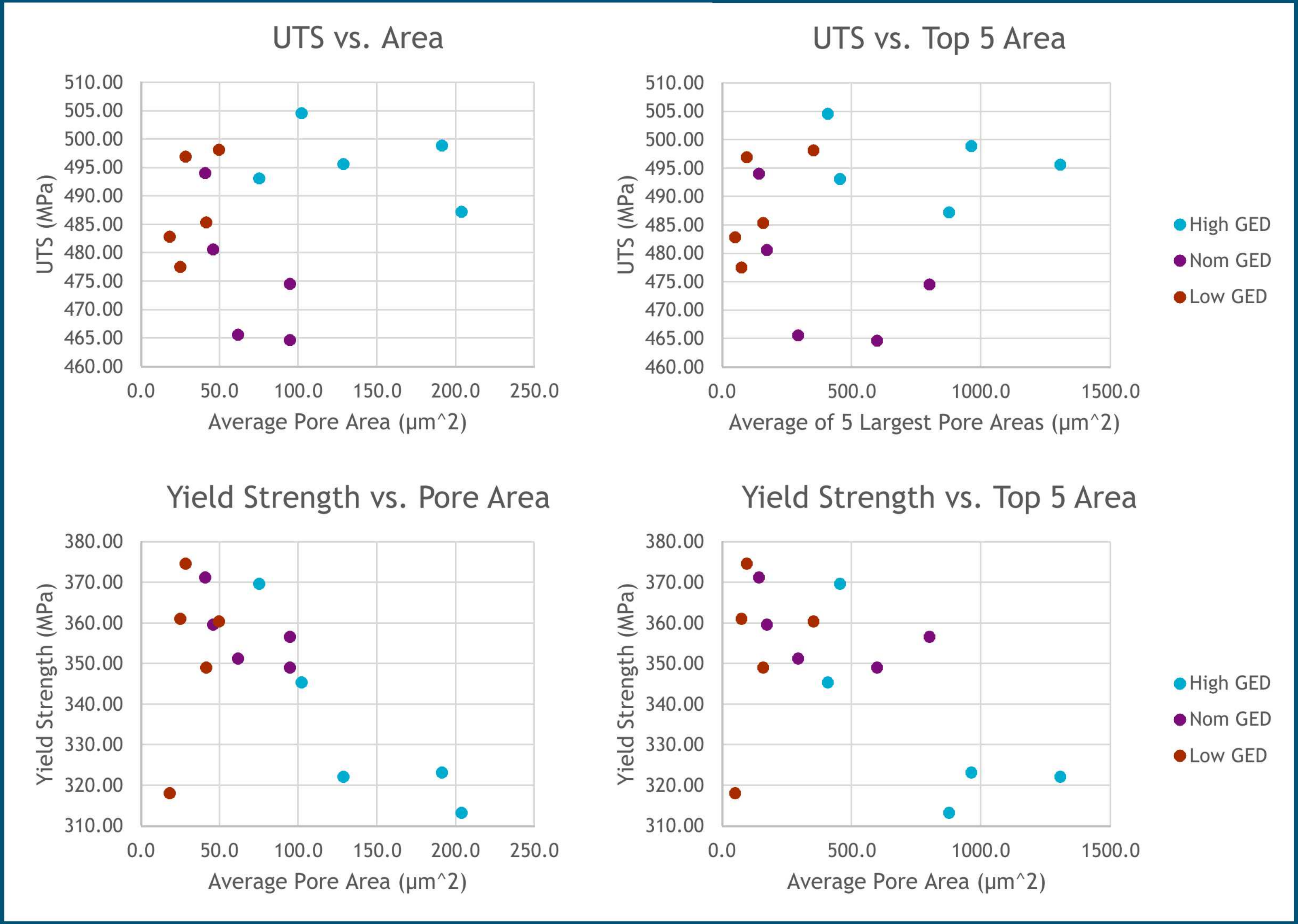
Jost, Elliott, 7/23/2019

Mechanical Properties vs. Porosity

No significant trend between ultimate tensile strength (UTS) and pore area.

This is consistent with what is expected based on UTS being generally unaffected by heterogeneities in AM samples.

Yield Strength drops up to 18% with high GED input when compared to low GED.

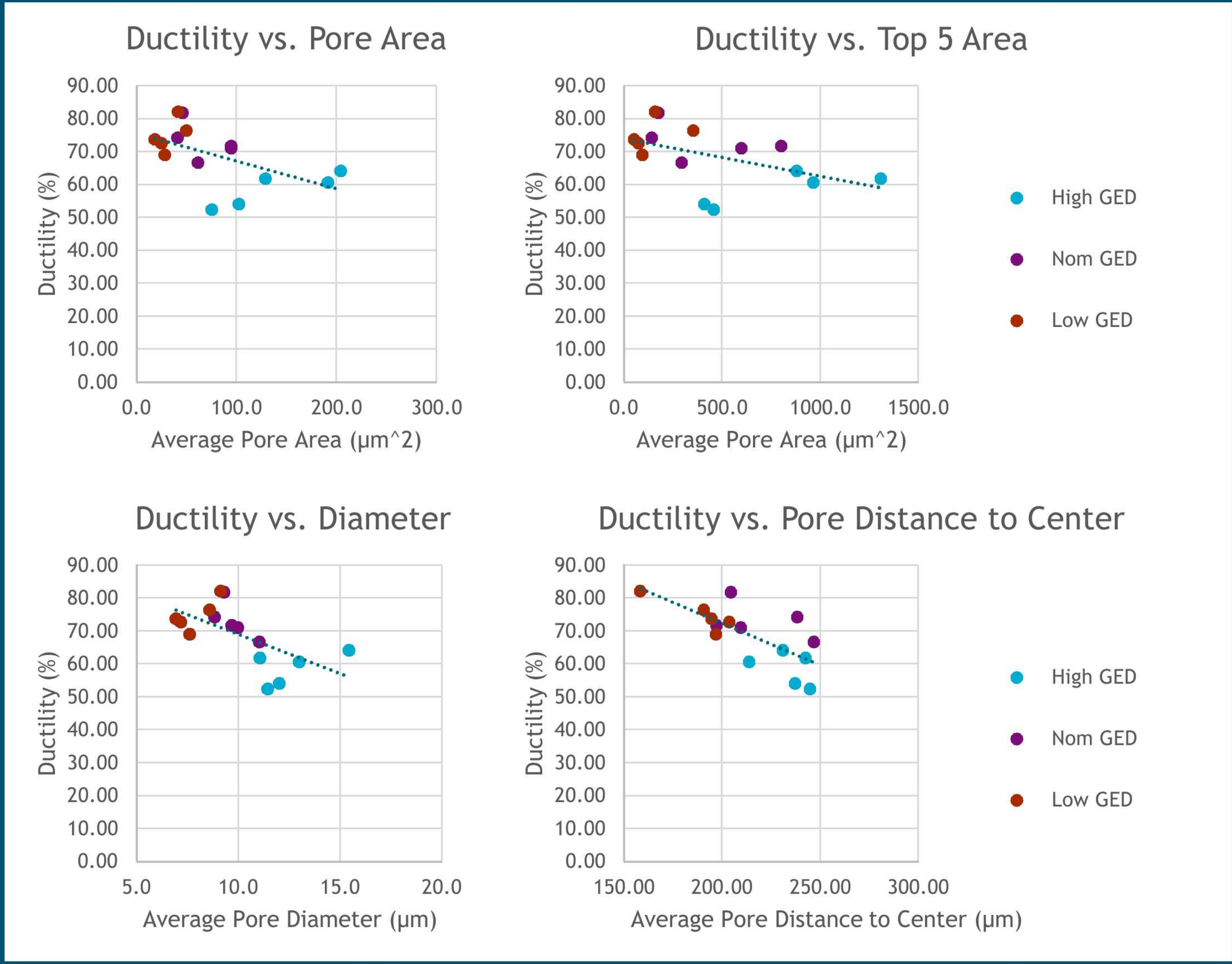


Ductility vs. Porosity

Ductility is negatively affected by pore area.

Ductility is negatively affected by 2D diameter of pore.

Ductility is negatively affected by pore distance to center.



It is hypothesized that pores have little effect on elastic properties, but large effects on plastic properties during tensile loading.

Mechanical Properties Summary

Variability in properties tended to be highest among High GED samples.

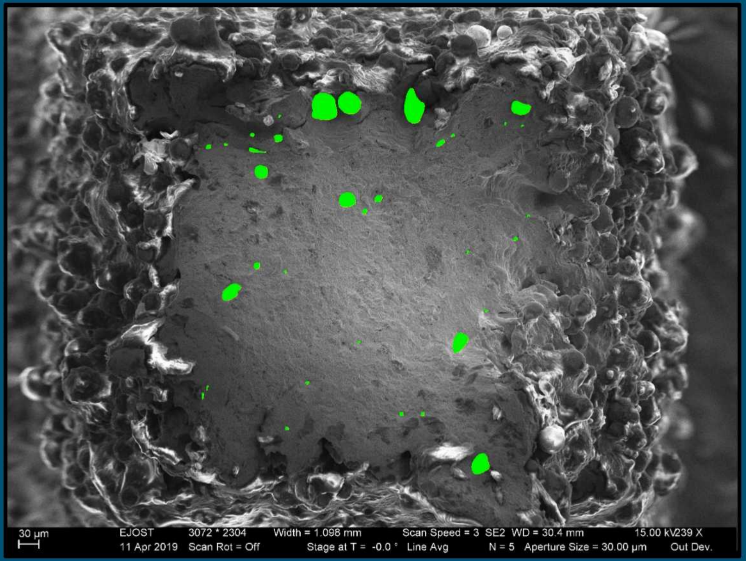
Ductility was lowered significantly in High GED samples, but was grouped more tightly.

	UTS (MPa)	Ductility (%)	Yield Strength (MPa)
High GED	490.3 ± 12.34	60.6 ± 3.99	336.9 ± 20.96
Nominal GED	481.0 ± 9.66	70.9 ± 4.62	363.6 ± 7.66
Low GED	493.7 ± 7.28	73.6 ± 4.53	366.1 ± 12.90

Conclusions

1. Properties are influenced by GED. High GED input results in decreased ductility and yield strength.
2. Higher-than-prescribed energy input is more detrimental than lower-than-prescribed energy input.
3. Largest, keyhole pores dominated effects on performance.

   → Thresholds can be set for inspection and qualification.



Future Work:

1. Volumetric porosity measurements (CT) can be correlated to performance for similar measurements of entire volumes.
2. Investigation of porosity size effects on differently-sized parts.
3. Investigation of effects with non-spatially-uniform pore distributions.
4. Development of models to predict location of failure.

Questions?