



Simulations to understand the effects of pores on the mechanical behavior of materials produced using powder bed fusion process

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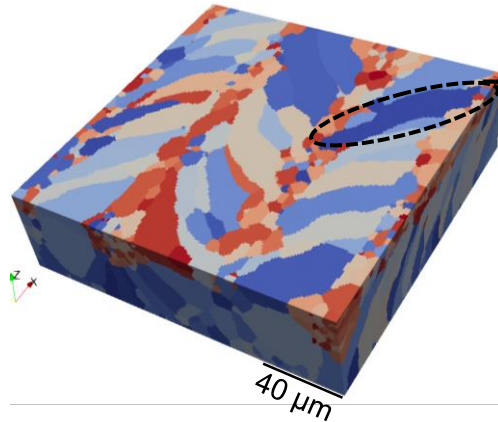
- Process-Structure-Performance Framework
- Process-Specific Defects in selective laser melting (SLM) additive manufacturing (AM) process
- Idealized Keyhole/Entrapped gas pores
- Idealized Lack of Fusion (LoF) pores
- Influence of Pore Geometry on Strain Localization
- 3D Model of LoF pores
- Partial validation of the 3D LoF model

Process-Structure-Performance Framework

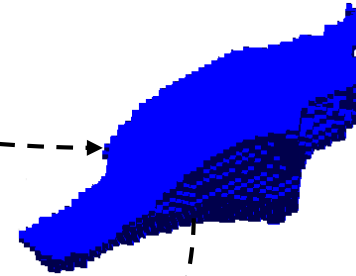
(Linking SPPARKS, DREAM.3D, Gmsh and ScIFEN)



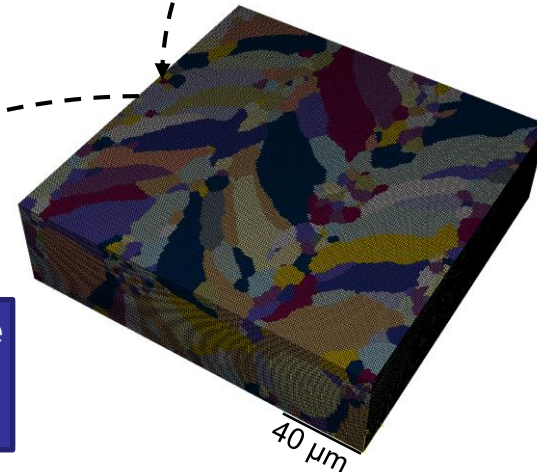
AM process simulation
SPPARKS¹



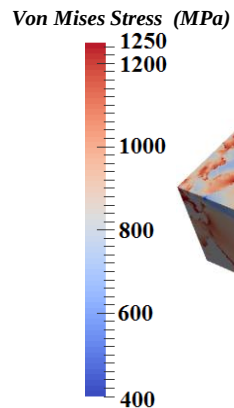
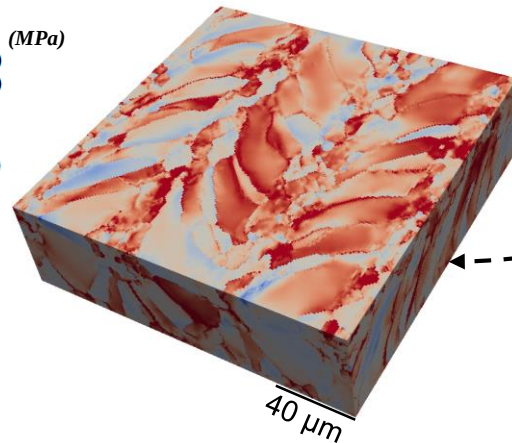
Use Output from SPPARKS
and generate .stl files
of grains using DREAM. 3D²



DREAM. 3D²/Gmsh³



Use ScIFEN⁴ to solve
for heterogeneous
stress/strain fields



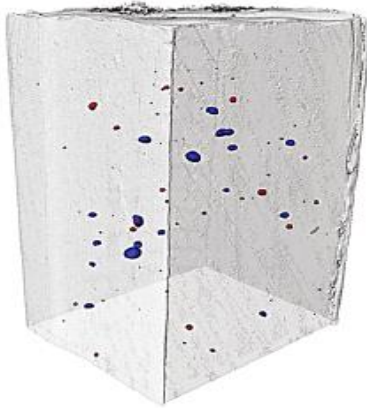
[1] spparks.sandia.gov
[2] dream3d.bluequartz.net

[3] <http://gmsh.info/>
[4] <https://software.nasa.gov/software/LAR-18720-1>

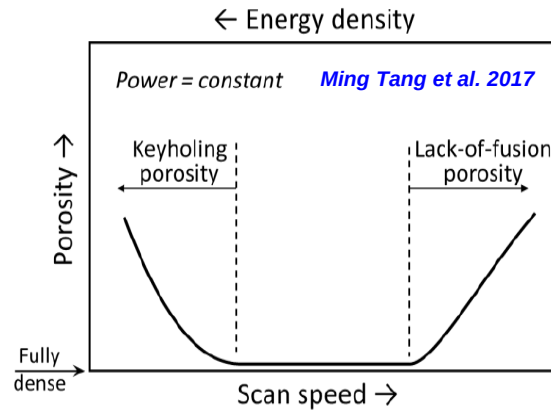
Process-Specific Defects in SLM



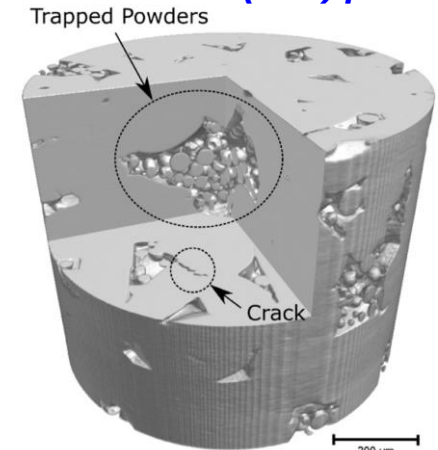
Keyhole porosity



Cunningham, R. et al. JOM, Vol. 69, No. 3, 2017

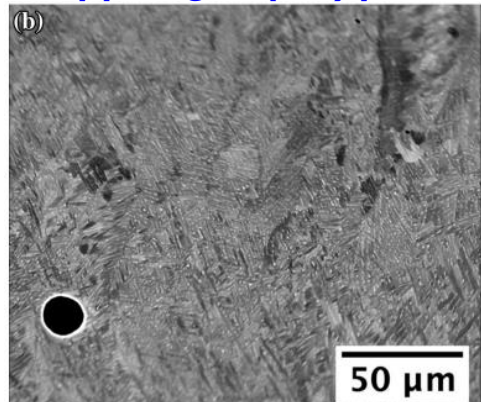


Lack of fusion (LoF) porosity



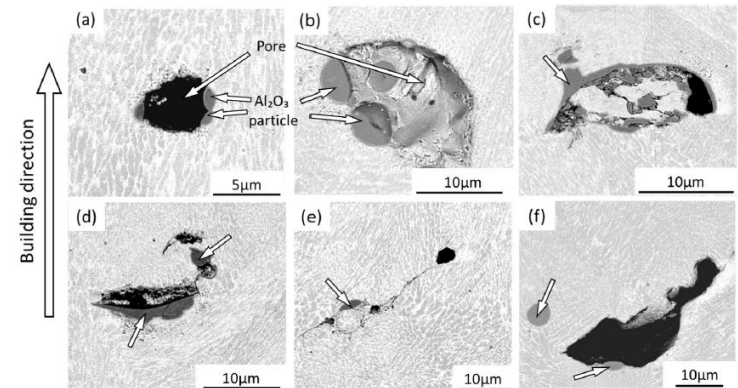
Kim, Moylan, et al., Addit Manuf (2017)

Entrapped gas (EG) porosity



JOM, Vol. 68, No. 3, 2016 DOI: 10.1007/s11837-015-1802-0

Oxide induced porosity

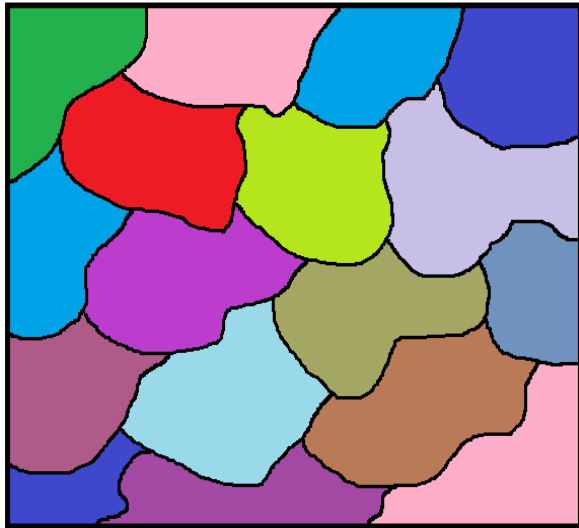


Tang et al. Int. J. Fatigue, Vol. 94, 2017, pp. 192-201

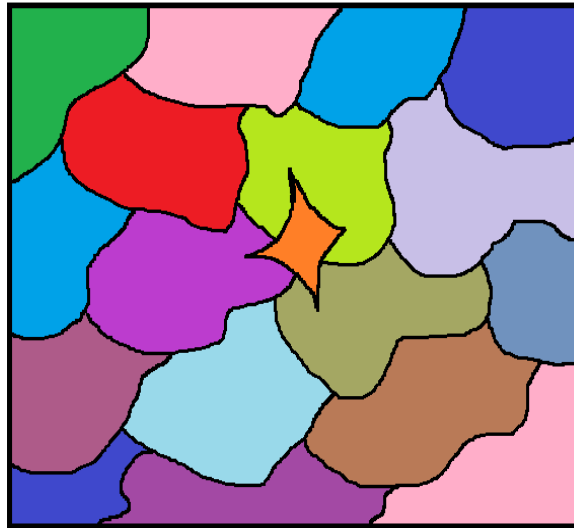
Porosity Insertion



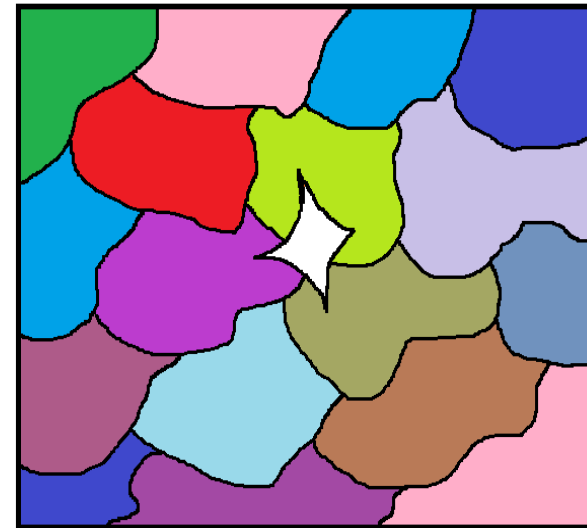
Pristine microstructure



Porosity region selected



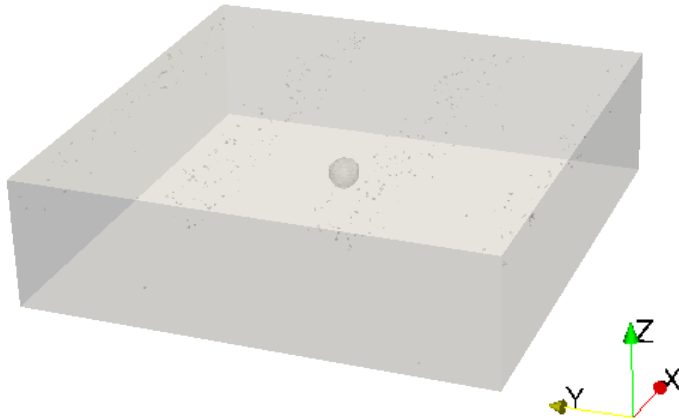
Pore inserted



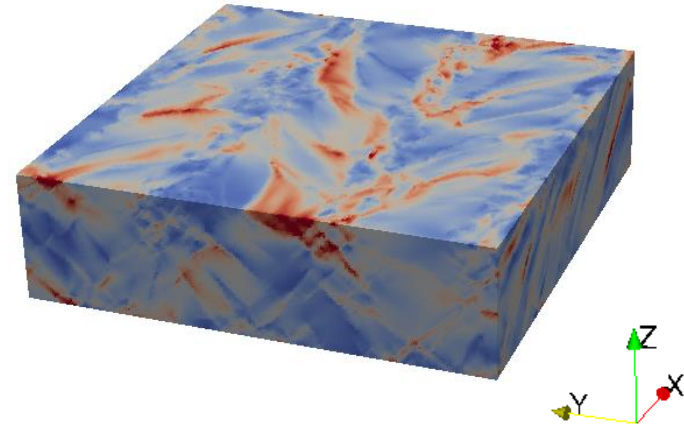
Idealized Keyhole/Entrapped Gas Pore



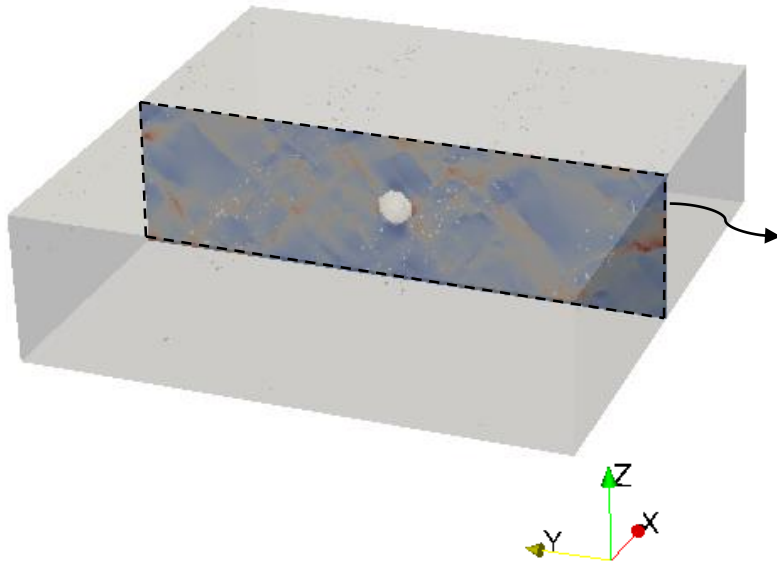
Microstructure volume showing the location of pore



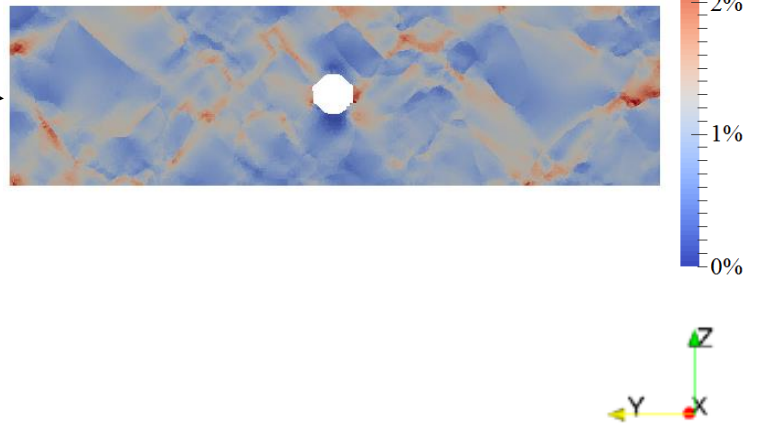
Heterogeneous strain field generated in the microstructure



Strain field on a plane passing through the pore



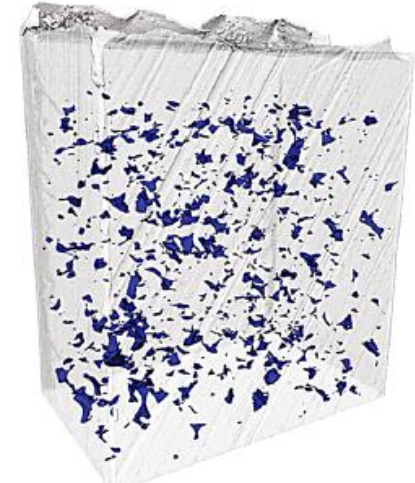
Cut section view of strain field around the pore



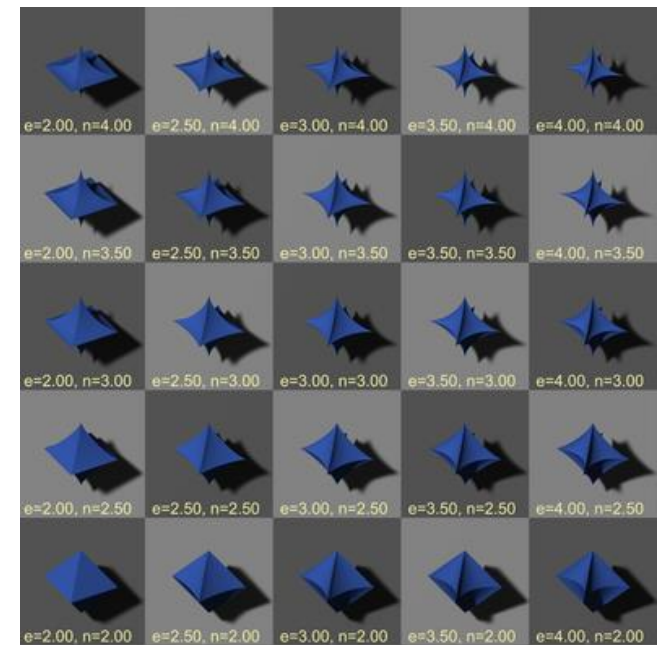
Simulating LoF Porosity



- Lack of high resolution data to characterize the shape attributes of LoF porosities.
- Irregular geometries of LoF porosities are approximated using super-ellipsoids.
- Equation of super-ellipsoids:
$$\left(\left| \frac{x}{A} \right|^{\frac{2}{e}} + \left| \frac{y}{B} \right|^{\frac{2}{e}} \right)^{\frac{e}{n}} + \left| \frac{z}{C} \right|^{\frac{2}{n}} \leq 1$$
- The sharp corners generated (for some specific types of super-ellipsoids) help study the stress concentrations and strain accumulation at those locations which could be detrimental for fatigue crack initiation.

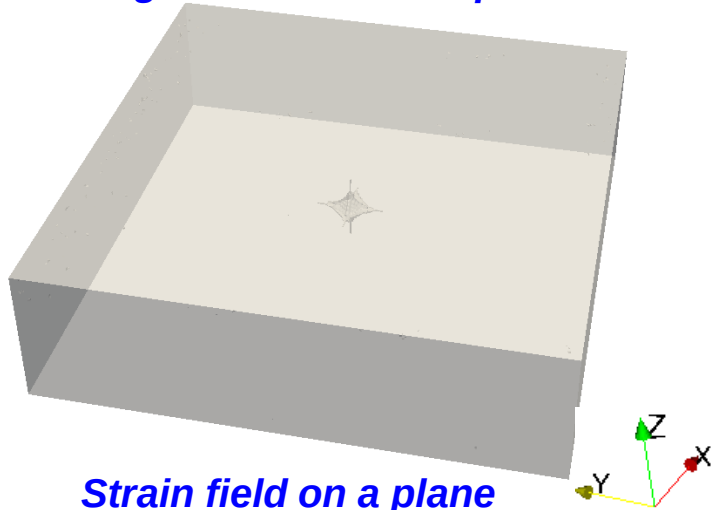


Cunningham, R. et al. JOM, Vol. 69, No. 3, 2017

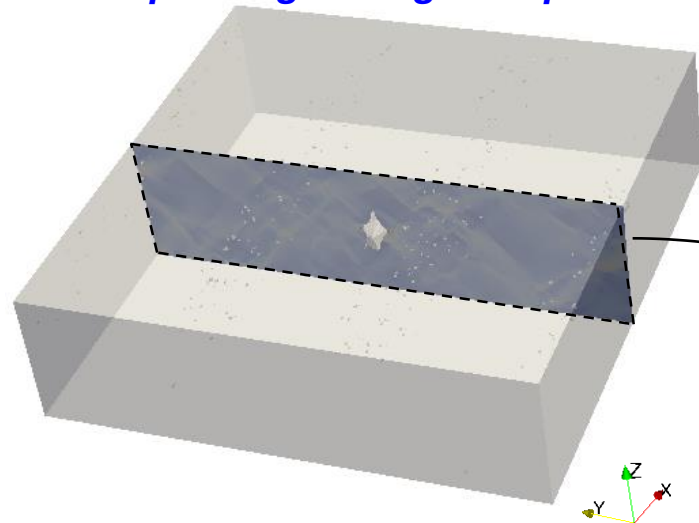


Idealized LoF Pores

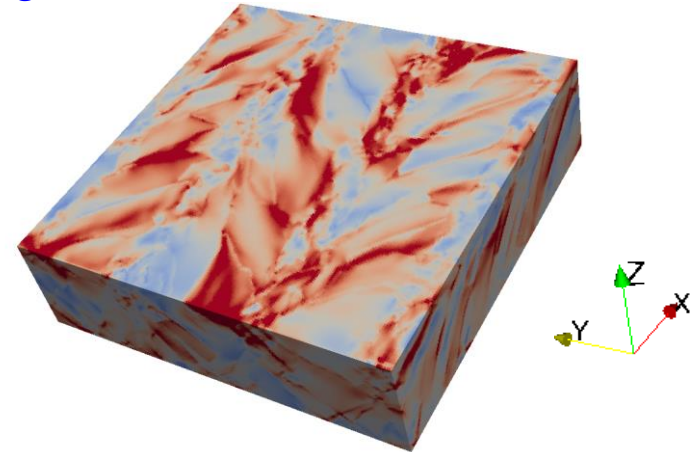
Microstructure volume showing the location the pore



Strain field on a plane passing through the pore

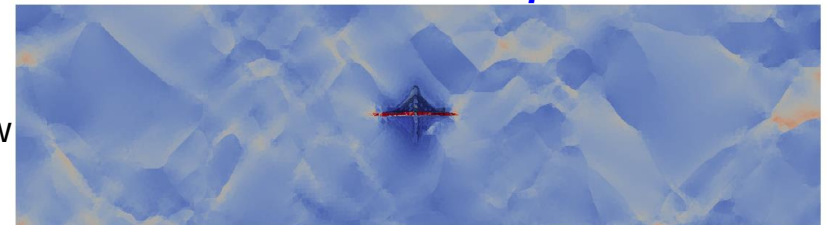


Heterogeneous strain field generated in the microstructure



Cut section view of strain field around the pore

Clip view



Slice view

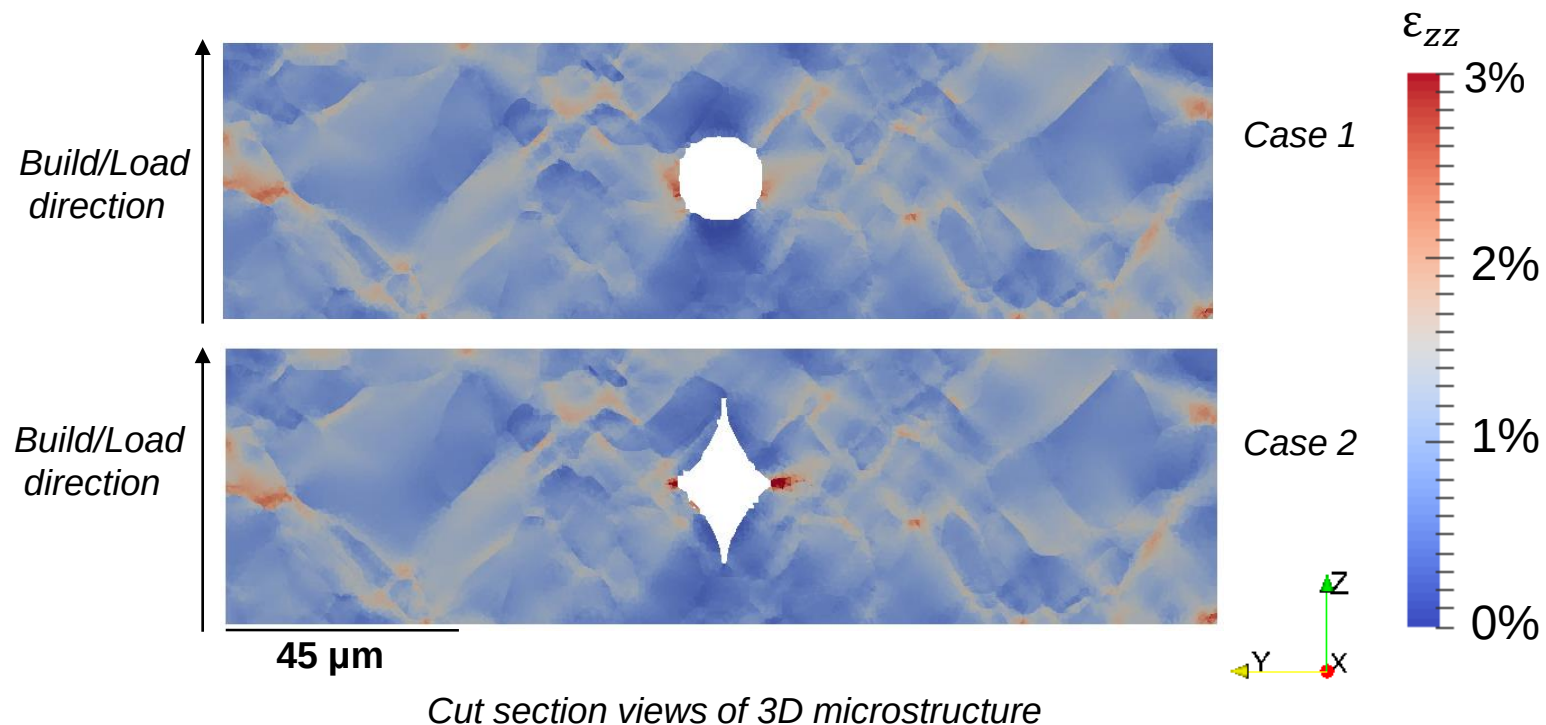


0 0.4% 0.8% 1.2% 1.6% 2%

ϵ_{zz} (strain component in loading direction)

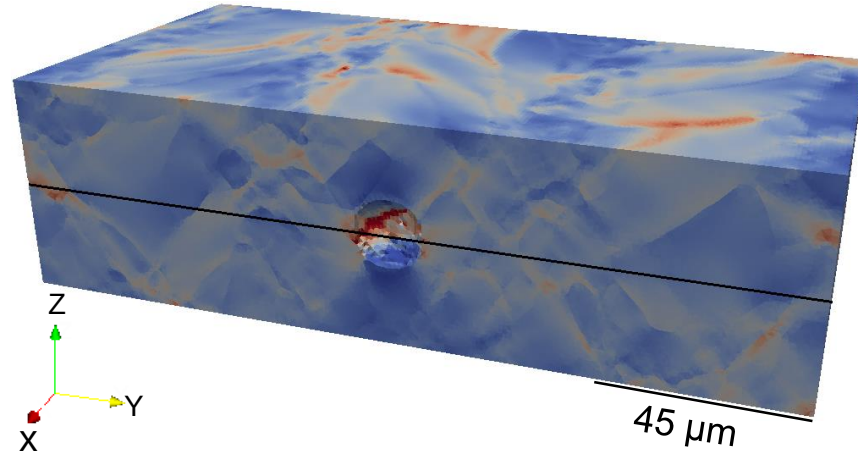
Influence of Pore Geometry on Strain Localization

- Material: IN 718
- LoF (super-ellipsoids) vs. keyhole (spherical) pores
- Surrounding microstructure is the same in both cases.
- Pore volume fraction is the same in both cases.
- Global strain applied: 1%
- Observation: Strain localization is intense for the irregular pore LoF with sharp corners compared to the idealized keyhole pore of the same size.

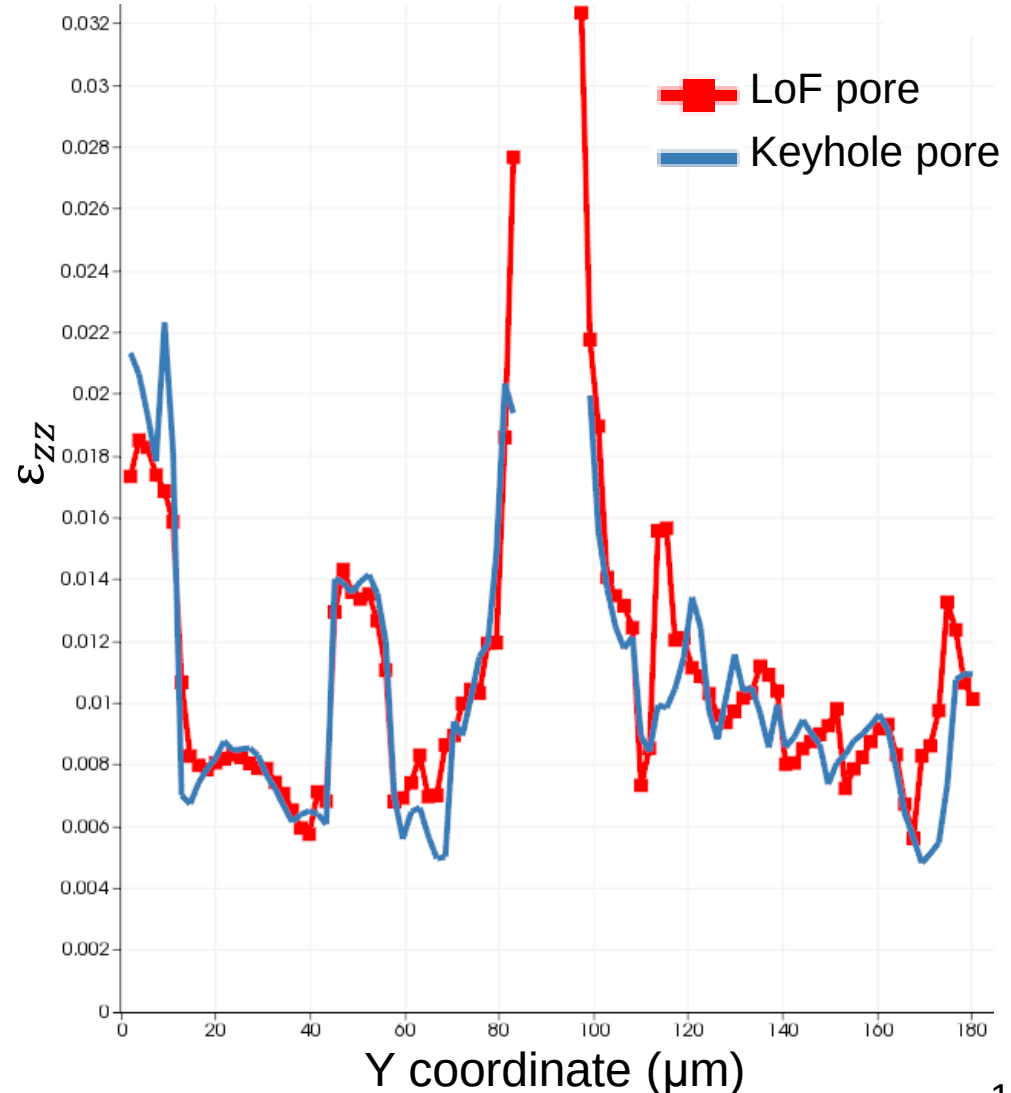
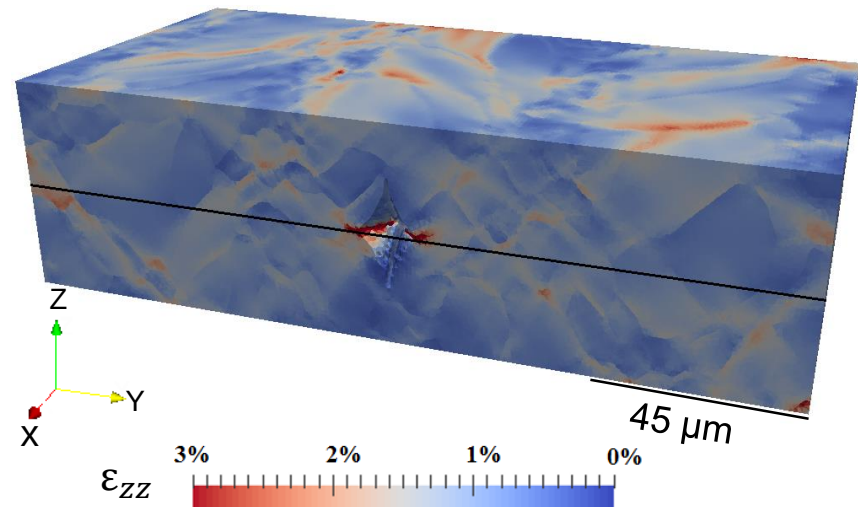


Influence of Pore Geometry on Strain Localization

Cut section view of the 3D microstructure with keyhole pore



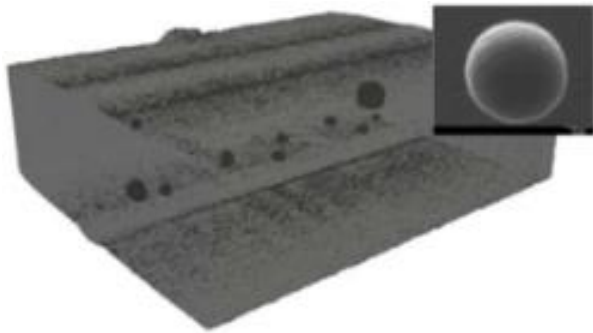
Cut section view of the 3D microstructure with LoF pore



Cluster of Idealized Keyhole/gas pores

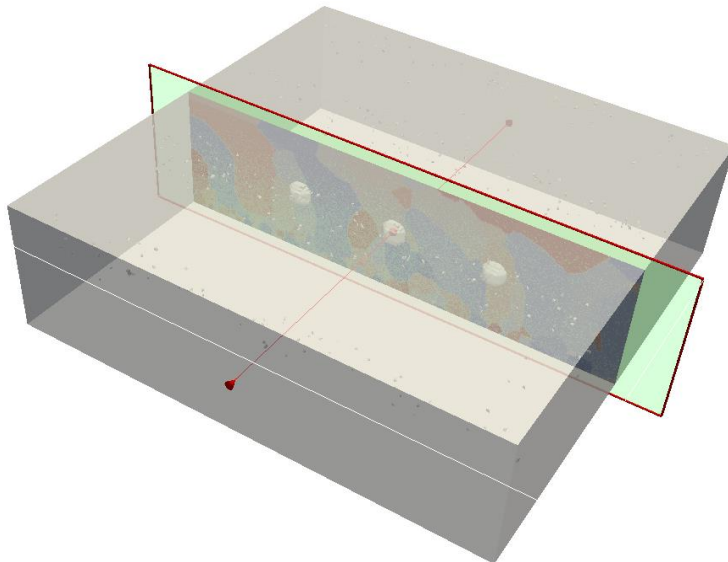


Keyhole pore distribution reconstructed from X-ray tomography

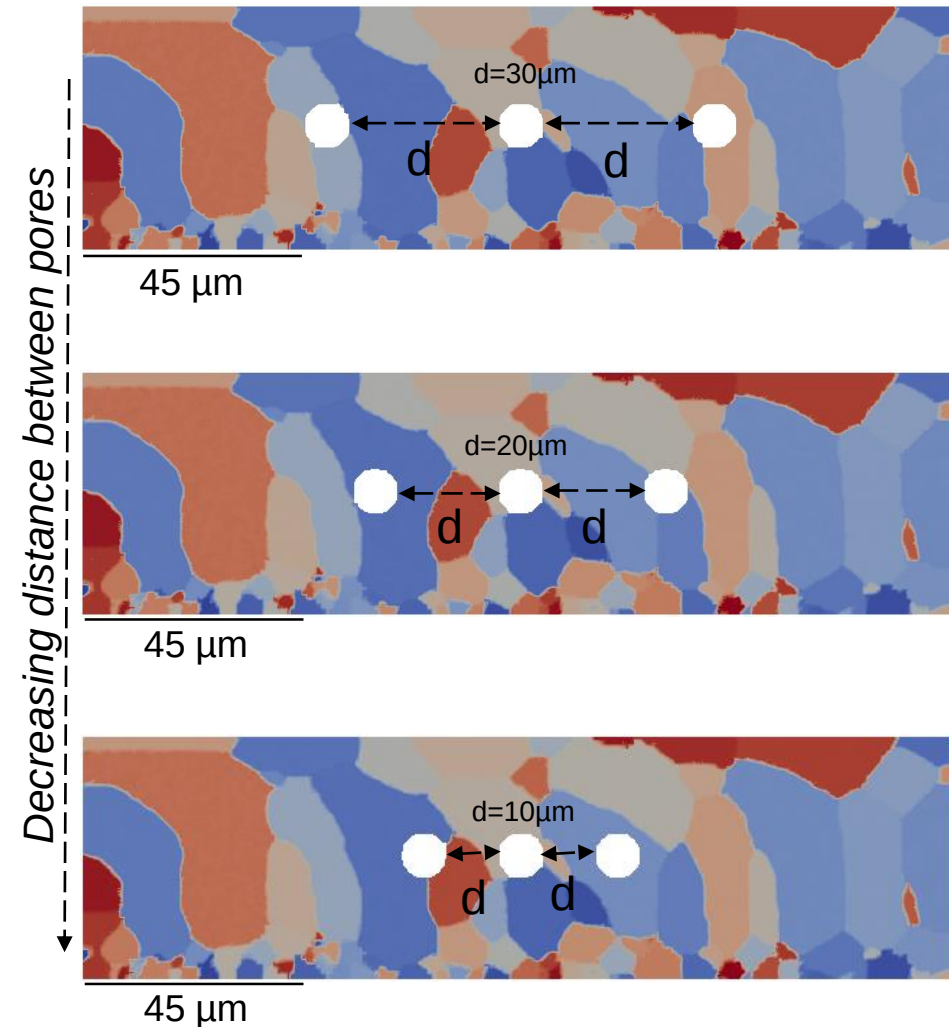


C. Panwisawas et al. / Acta Materialia 126 (2017) 251-263

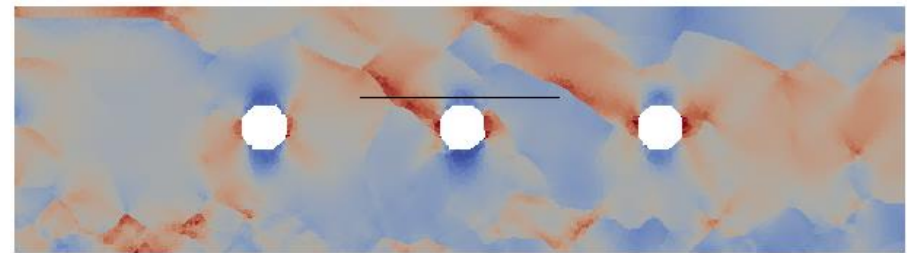
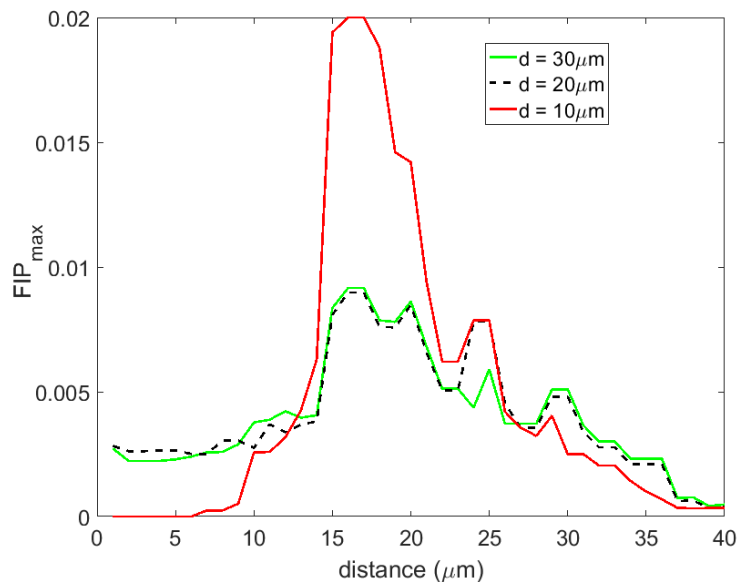
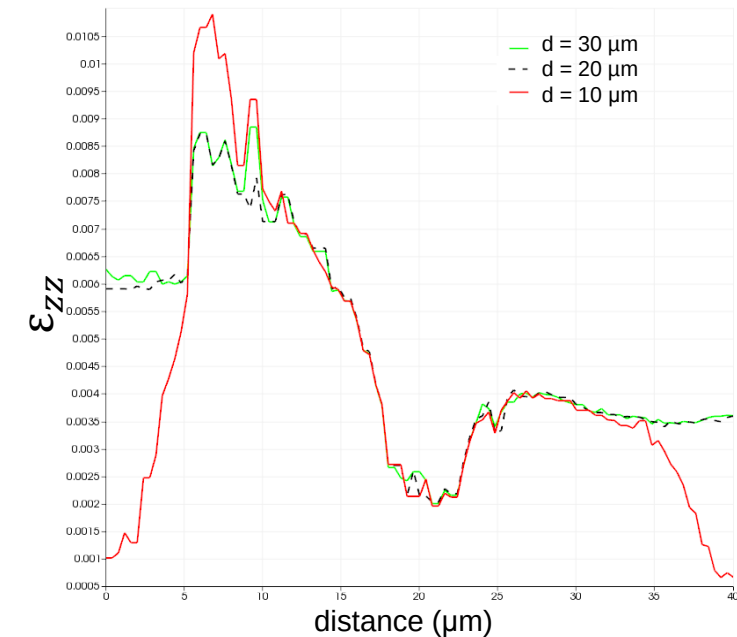
3D microstructure domain showing user-specified spherical pores whose centers are collinear



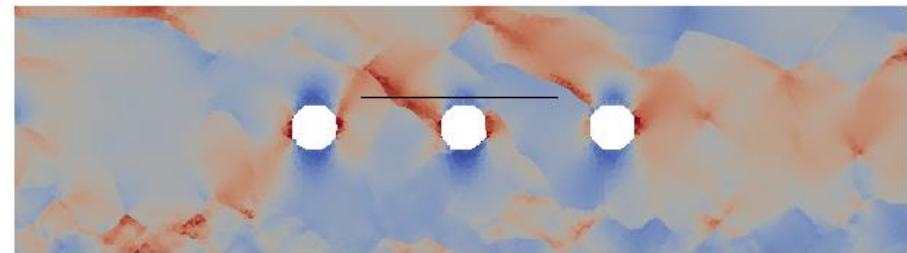
- 2D section of a 3D microstructure
- 3 cases that show varying distance between pores



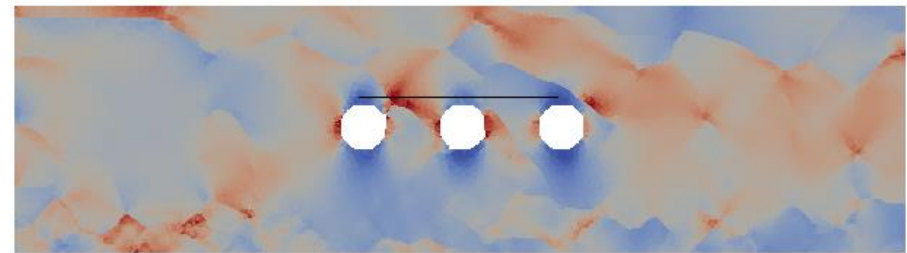
Cluster of Idealized Keyhole/gas pores



45 μm



45 μm



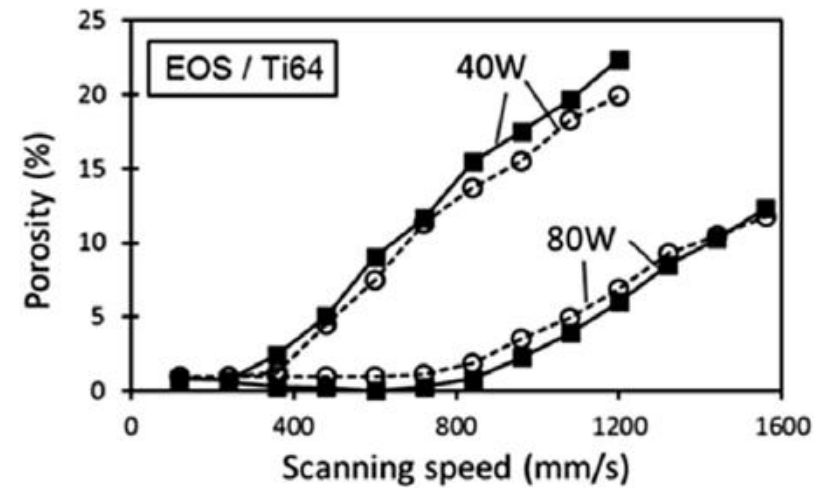
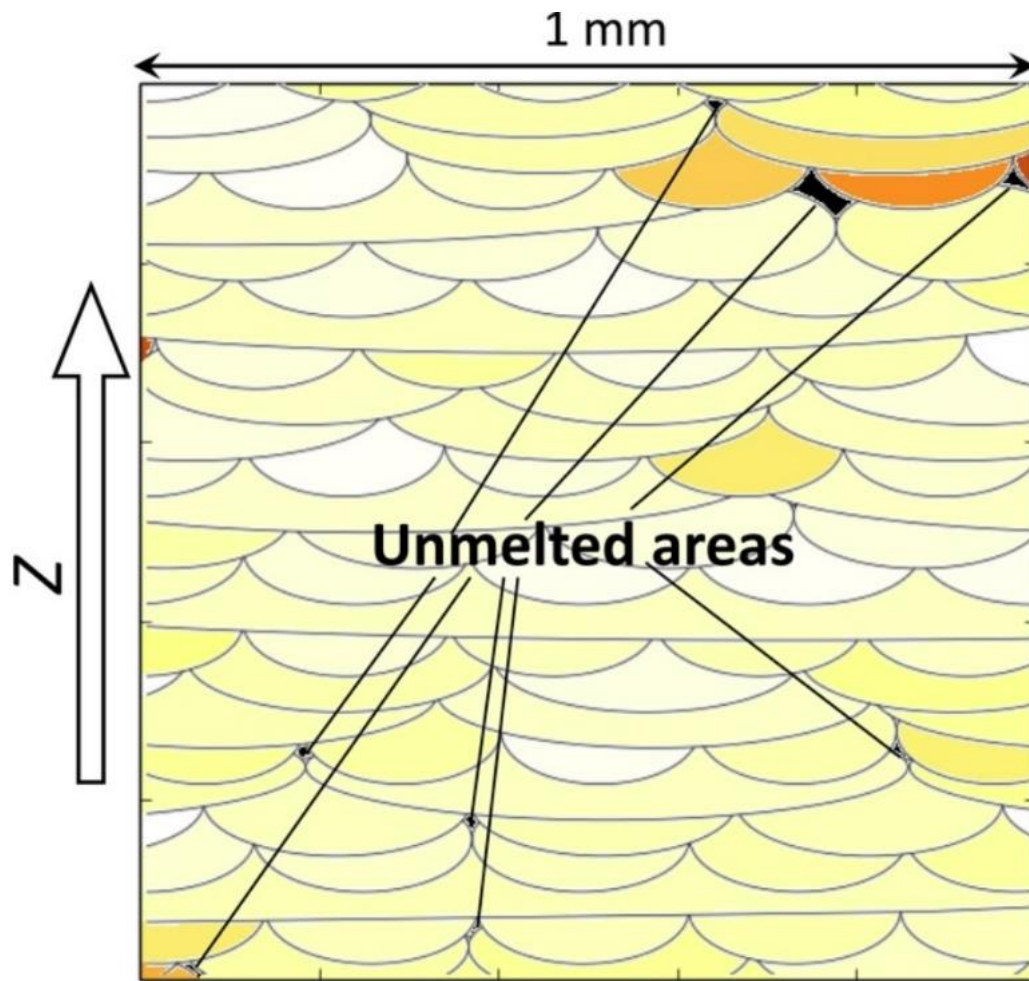
45 μm

ϵ_{zz} 0% 0.5% 1%

- Strain localization at grain boundary and slip originating from the pore, interact to magnify the fatigue crack driving forces (FIP_{max}) for the case when the distance between pores is equal to the diameter of the pores ($d=10\mu m$)
- No significant effect on the strain localization (ϵ_{zz}) or FIP_{max} was observed for the cases $d=20\mu m$ and $d=30\mu m$

3D Lack-of-Fusion Porosity Prediction Model

2D LoF Porosity Prediction Model



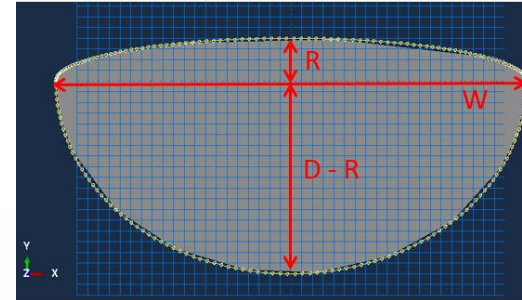
Single Scan Track

Rosenthal Equation:

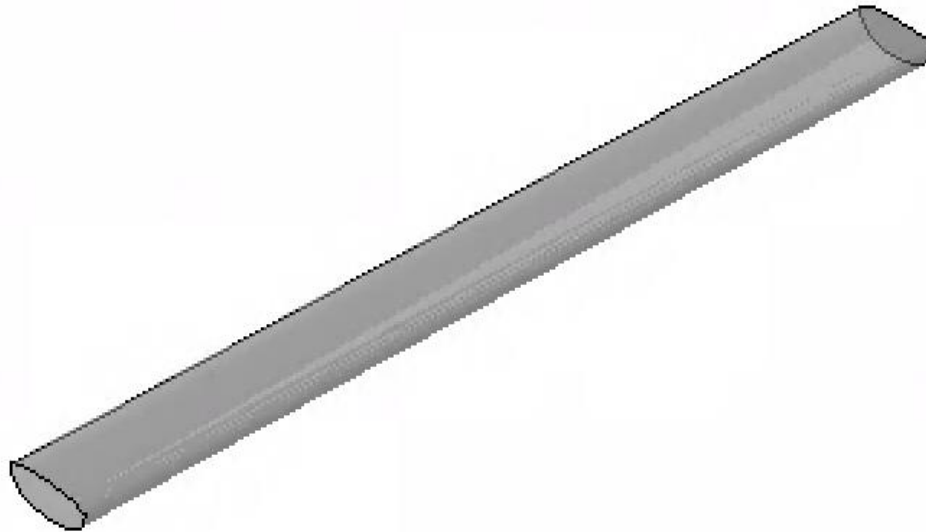
$$Q = \pi k (T_f - T_o) W + e \pi \rho C (T_f - T_o) V W^2 / 8$$

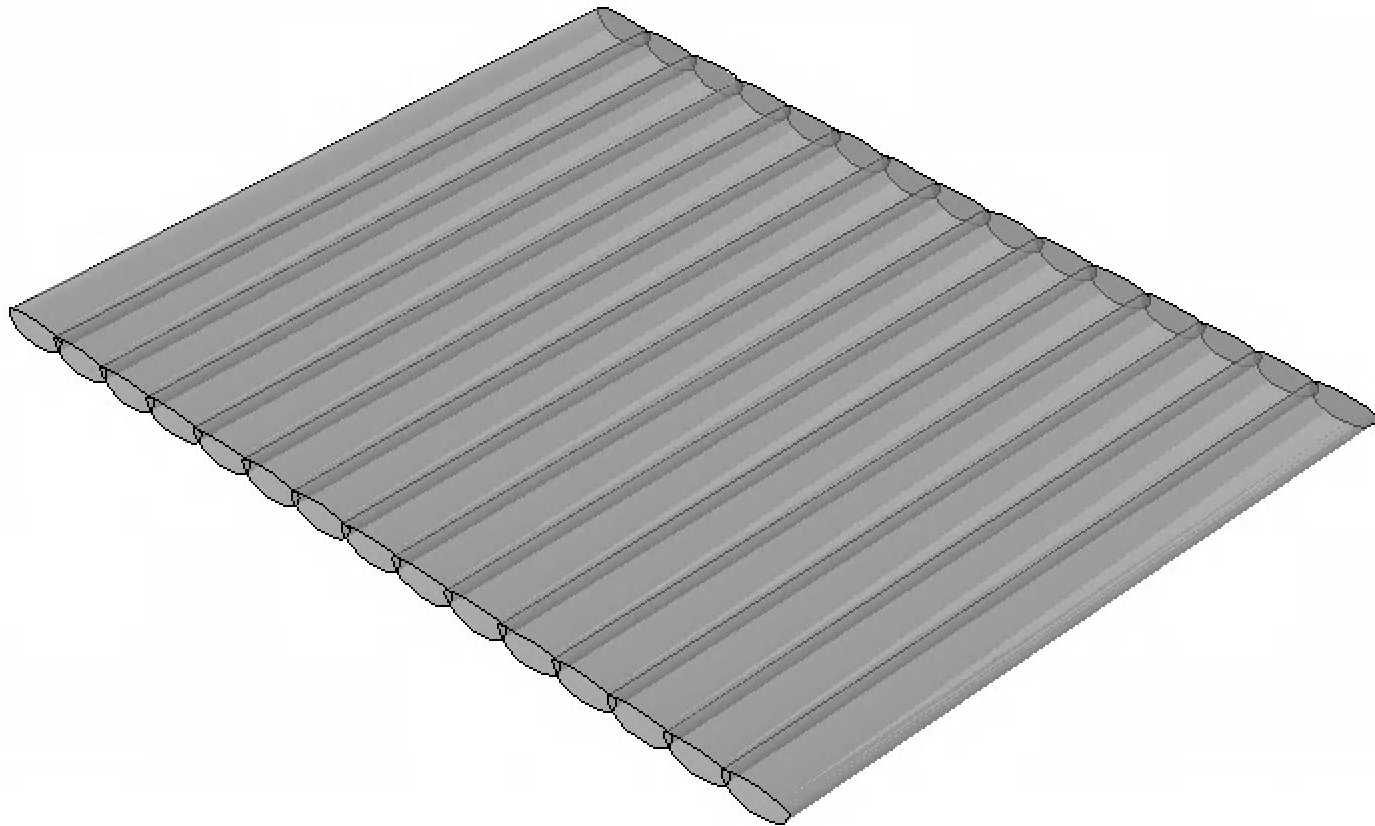
- Q Absorbed Power
- k Thermal Conductivity
- C Heat Capacity
- ρ Density
- T_f Melting Point
- T_o Ambient Temp

Cross-section of the melt pool

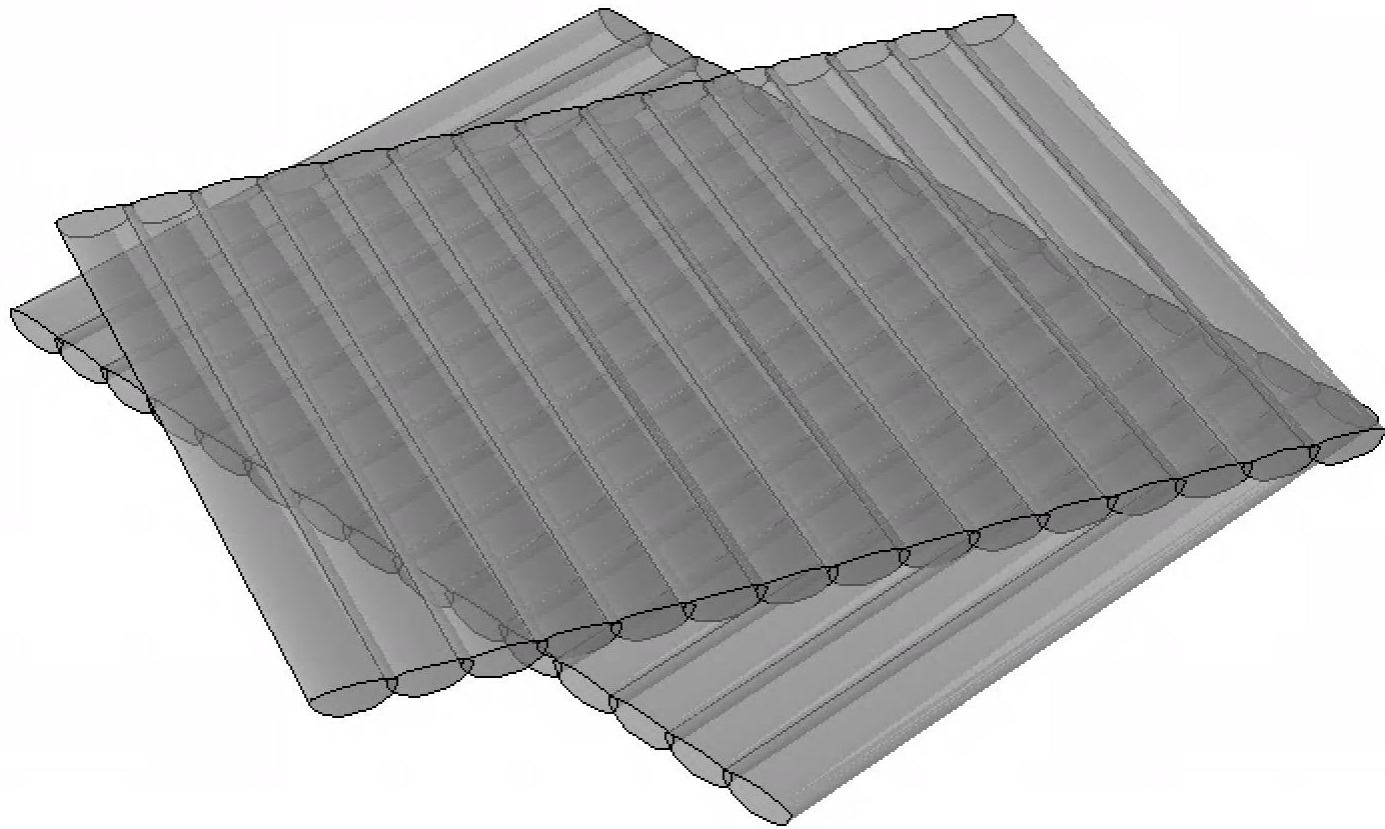


W = melt pool width
D = melt pool depth
R = bead height

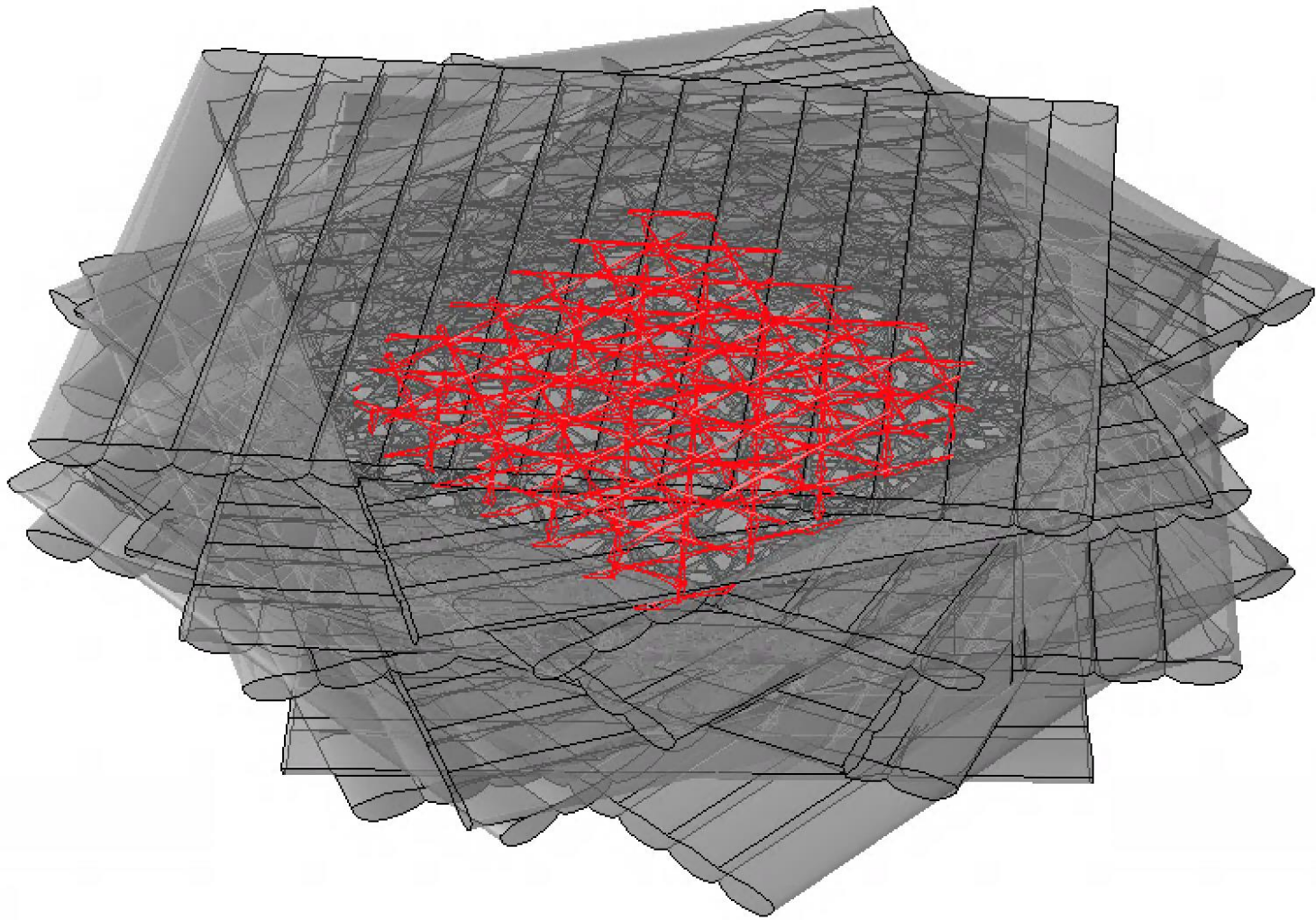


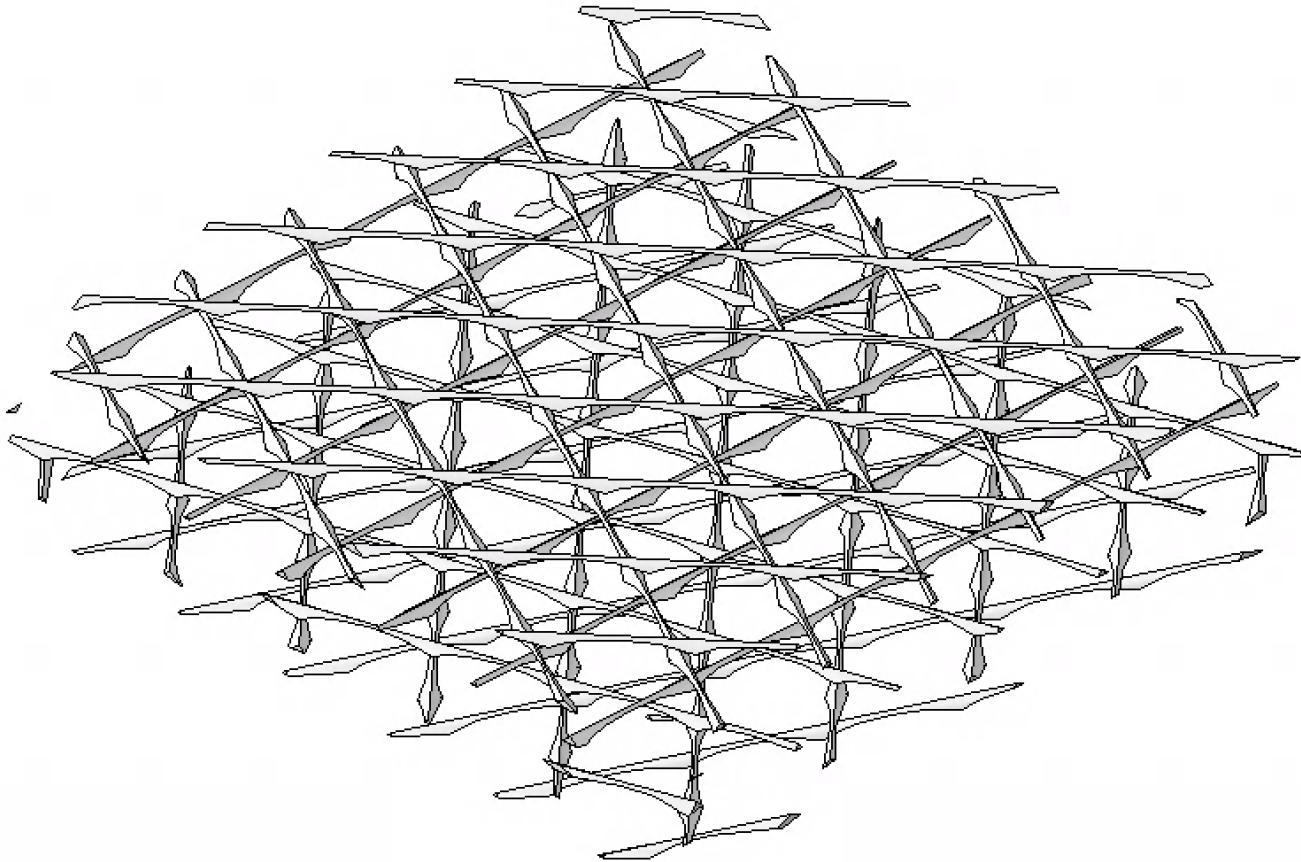


Two Layers



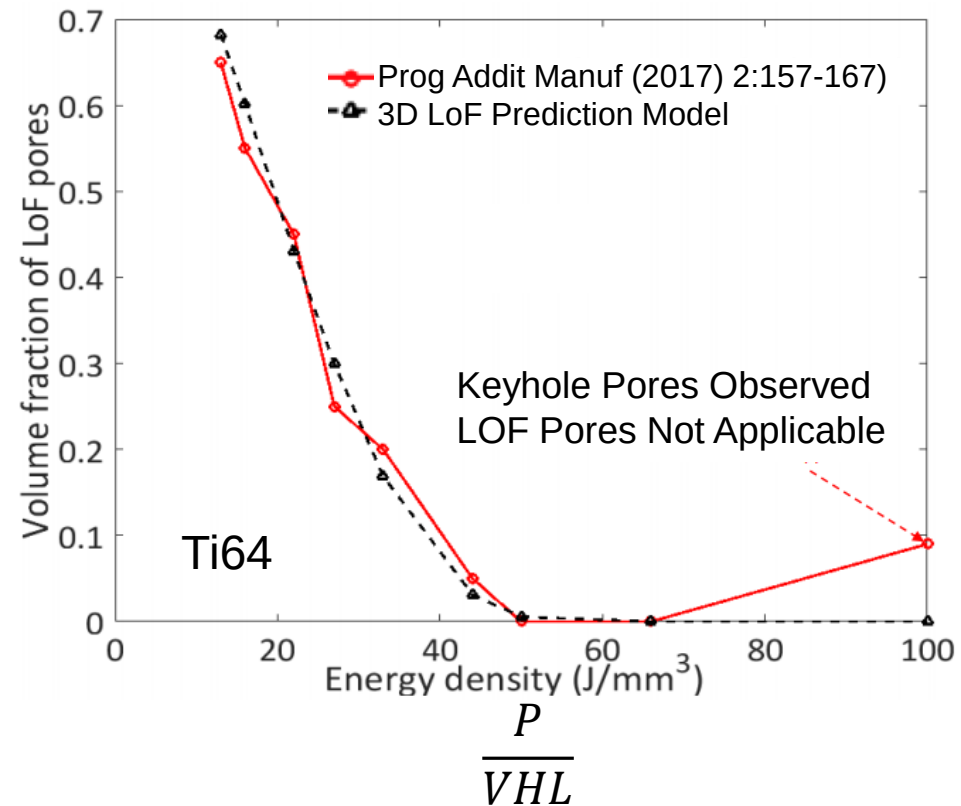
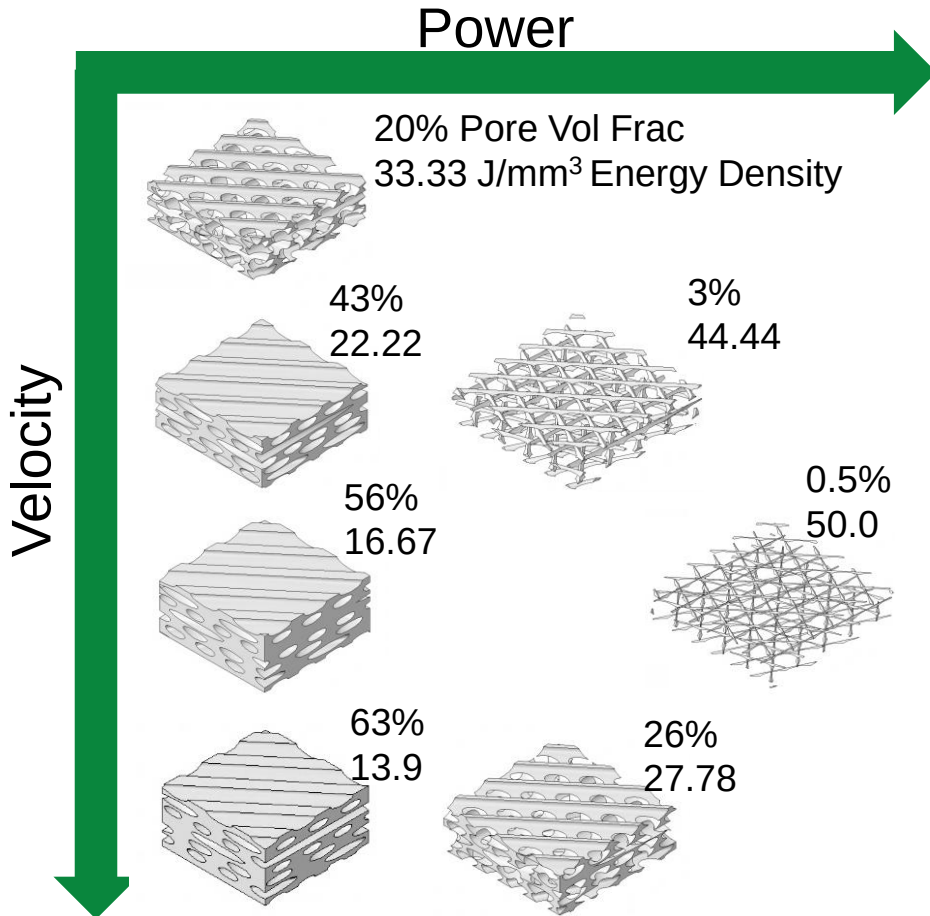
“Cut” Pores





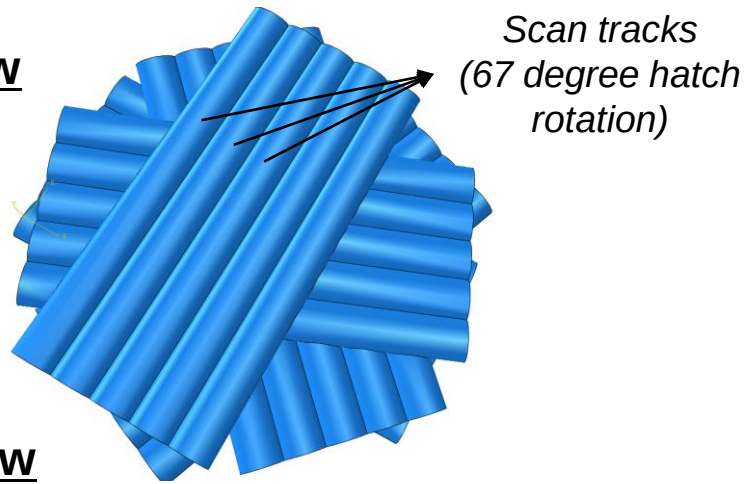
Validation: Volume Fraction of LoF Porosity

$$R = 10 \mu\text{m} \quad L = 30 \mu\text{m} \quad H = 100 \mu\text{m} \quad D/W = 0.4$$

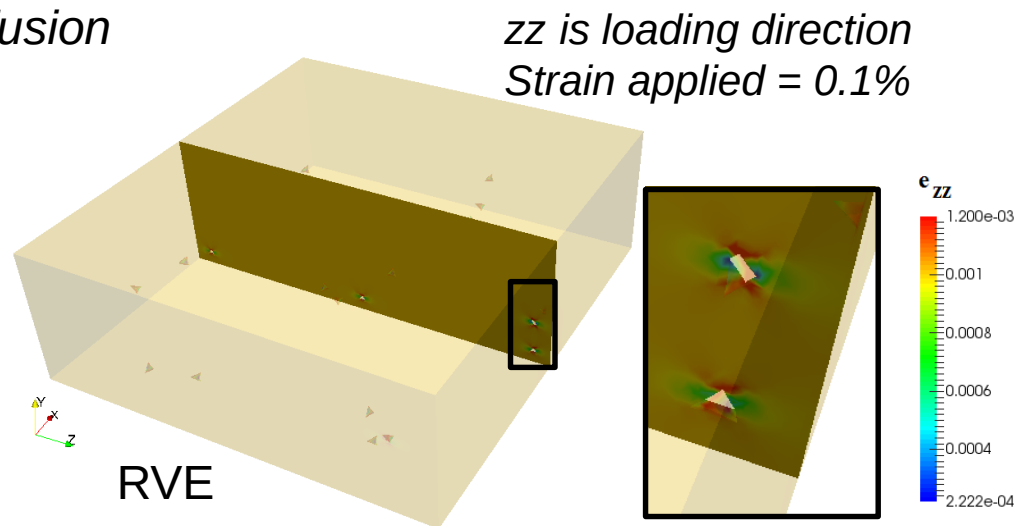
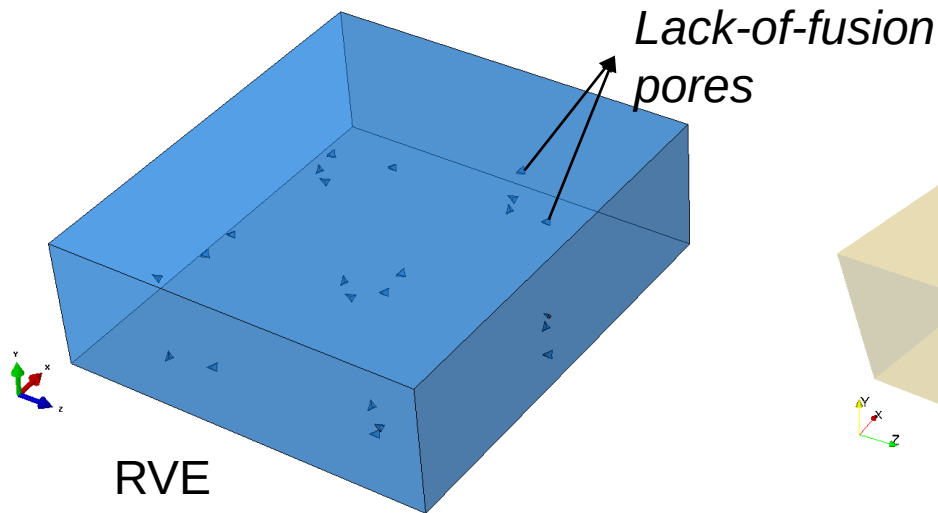
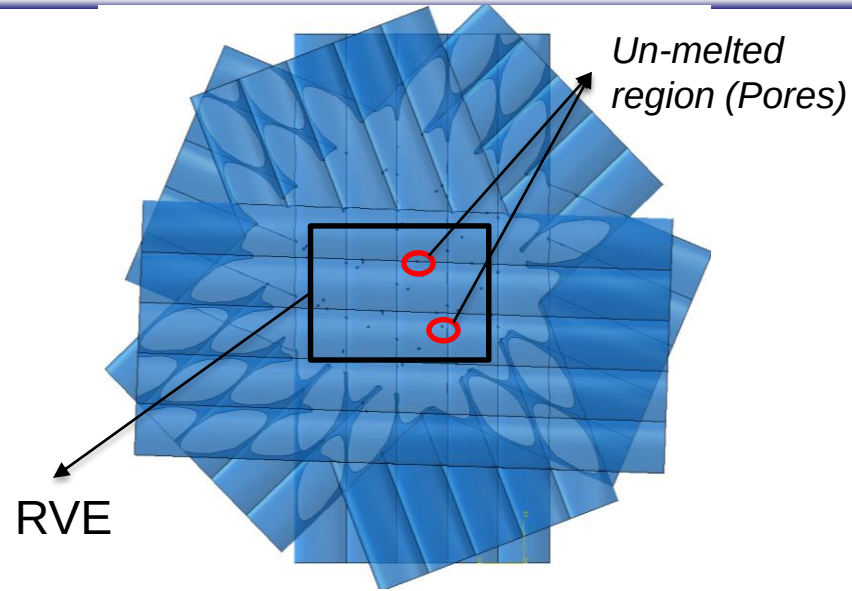
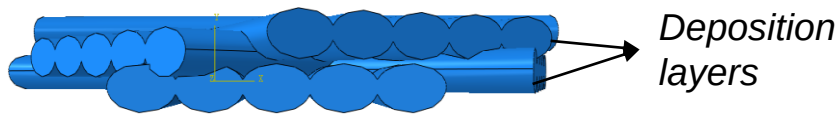


3D LoF Porosity Model overview

Top view



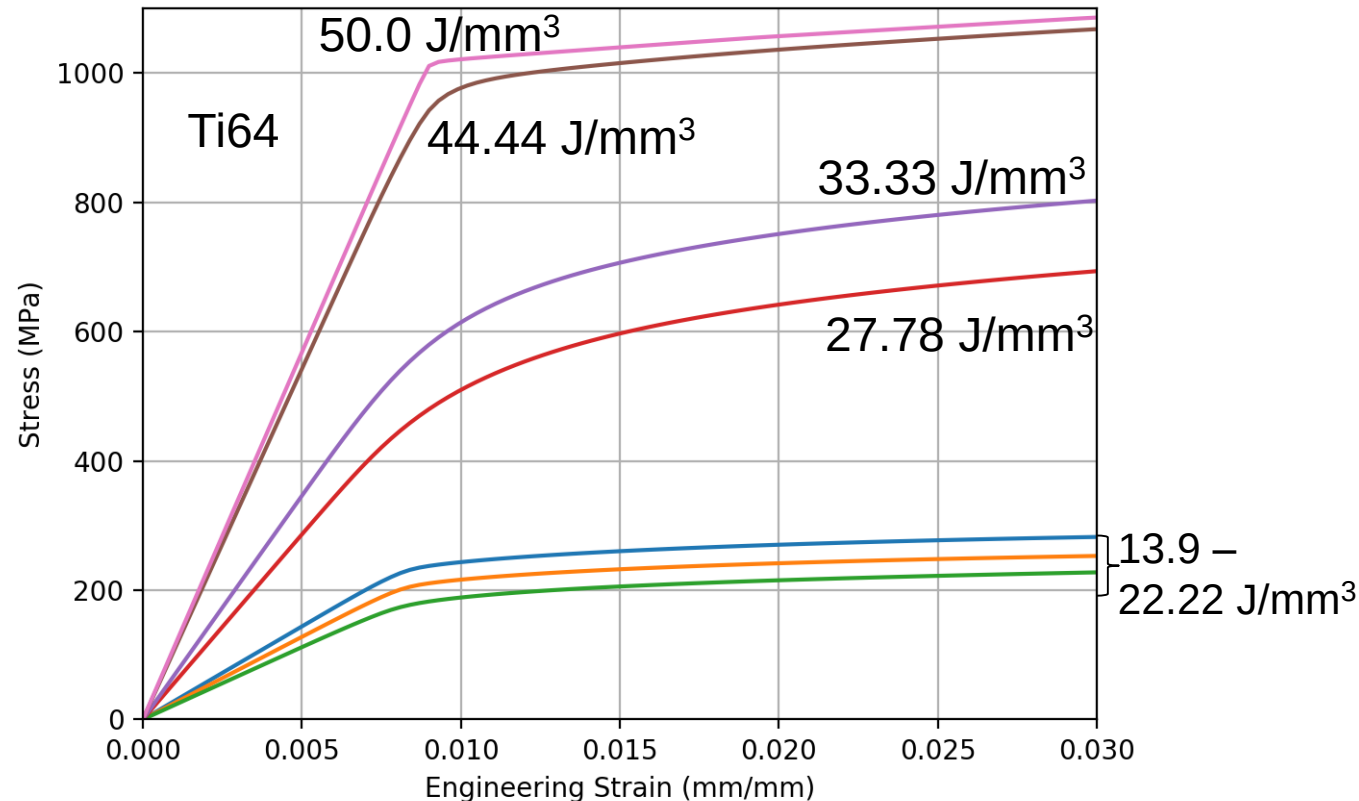
Side view



Stress-Strain behavior with varying energy density

$$R = 10 \mu\text{m} \quad L = 30 \mu\text{m} \quad H = 100 \mu\text{m} \quad D/W = 0.4$$

- LOF pores of varying energy density considered.
 - explicitly modelled
 - not homogenized
- No microstructure
- The solid is elastic-plastic, fully dense.
 - LEI
 - J2 plasticity



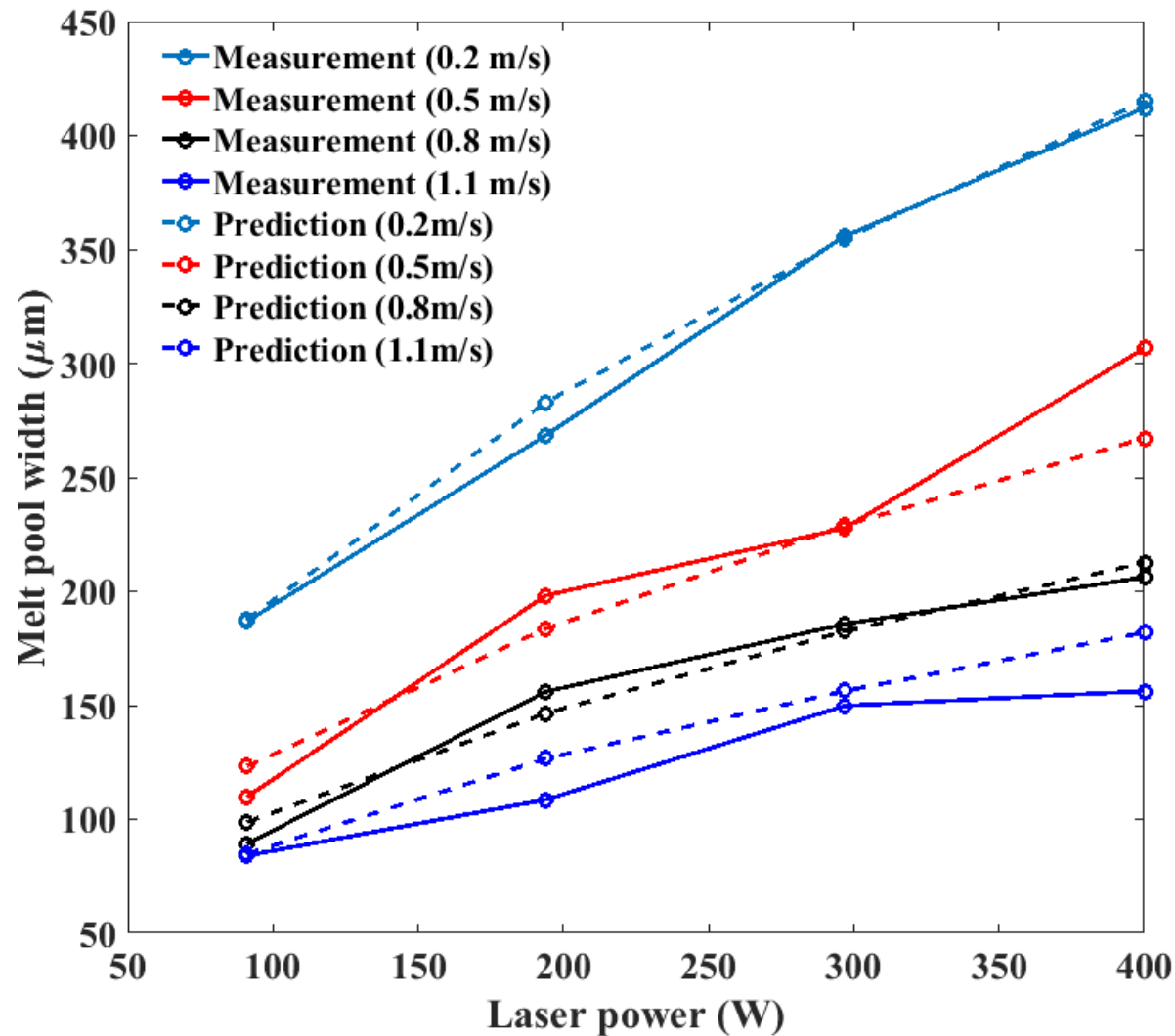
- Pull models in simple tension out to 3% strain.
- Load applied parallel to build direction.

- Overview of a high-fidelity Process-Structure-Property (PSP) framework
- Strain localizations surrounding idealized keyhole and LoF pores has been studied using the PSP framework
- Significant increase in strain localization and FIP values was observed as the distance between keyhole pores approaches the size of the pores.
- 3D LoF porosity prediction framework
- Partial validation of the 3D LoF model
- Finite element simulations by explicitly considering 3D LoF porosities
- Effect of porosity on macroscopic stress-strain behavior
- LoF porosity decreases performance

Thank you!

BACK UP

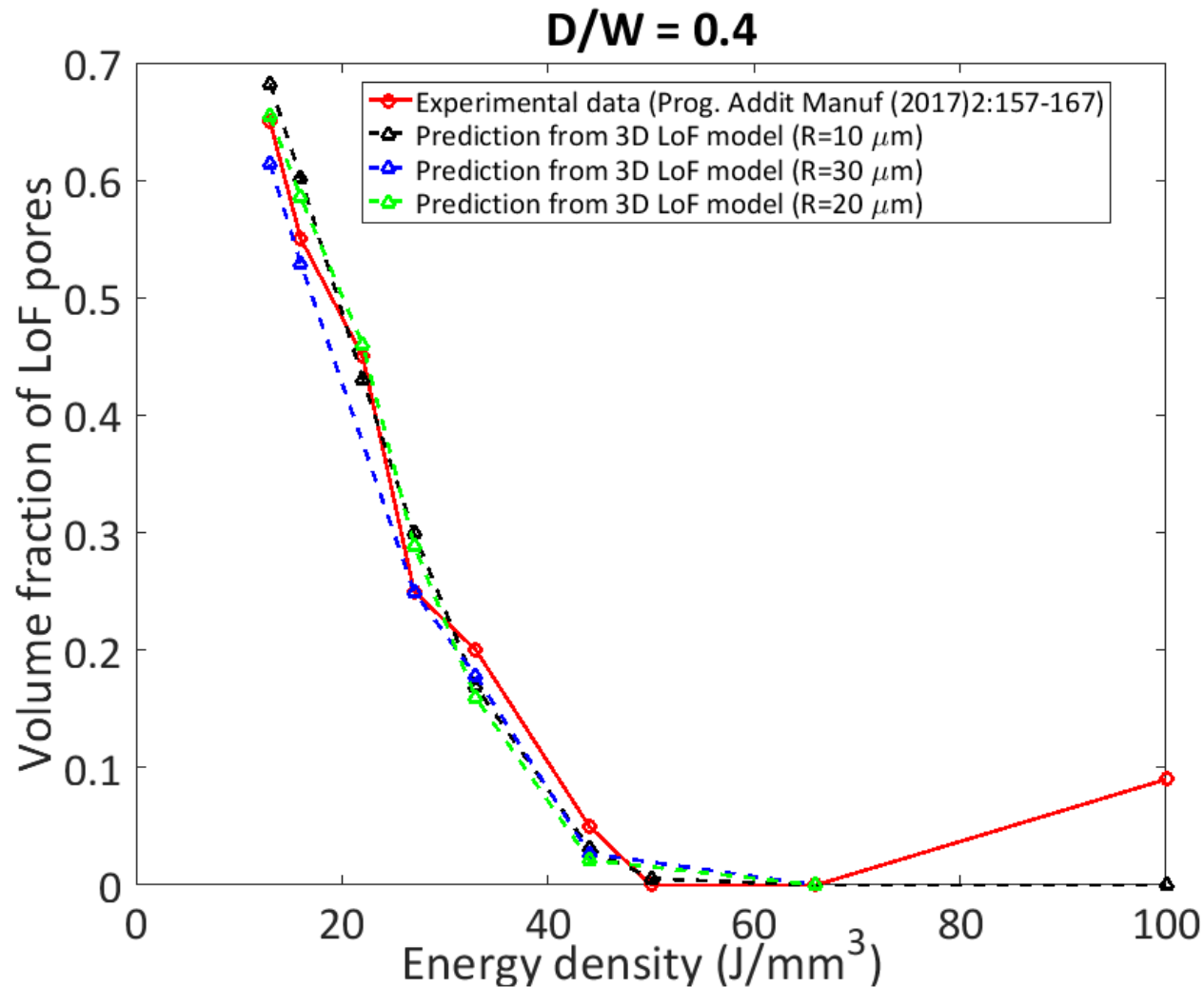
Validation of Rosenthal Equation



Experimental melt pool data has been obtained from:

Kusuma, C., "The Effect of Laser Power and Scan Speed on Melt Pool Characteristics of Pure Titanium and Ti-6Al-4V alloy for Selective Laser Melting," Master's Thesis, Wright State Univ., Dayton, OH, 2016.

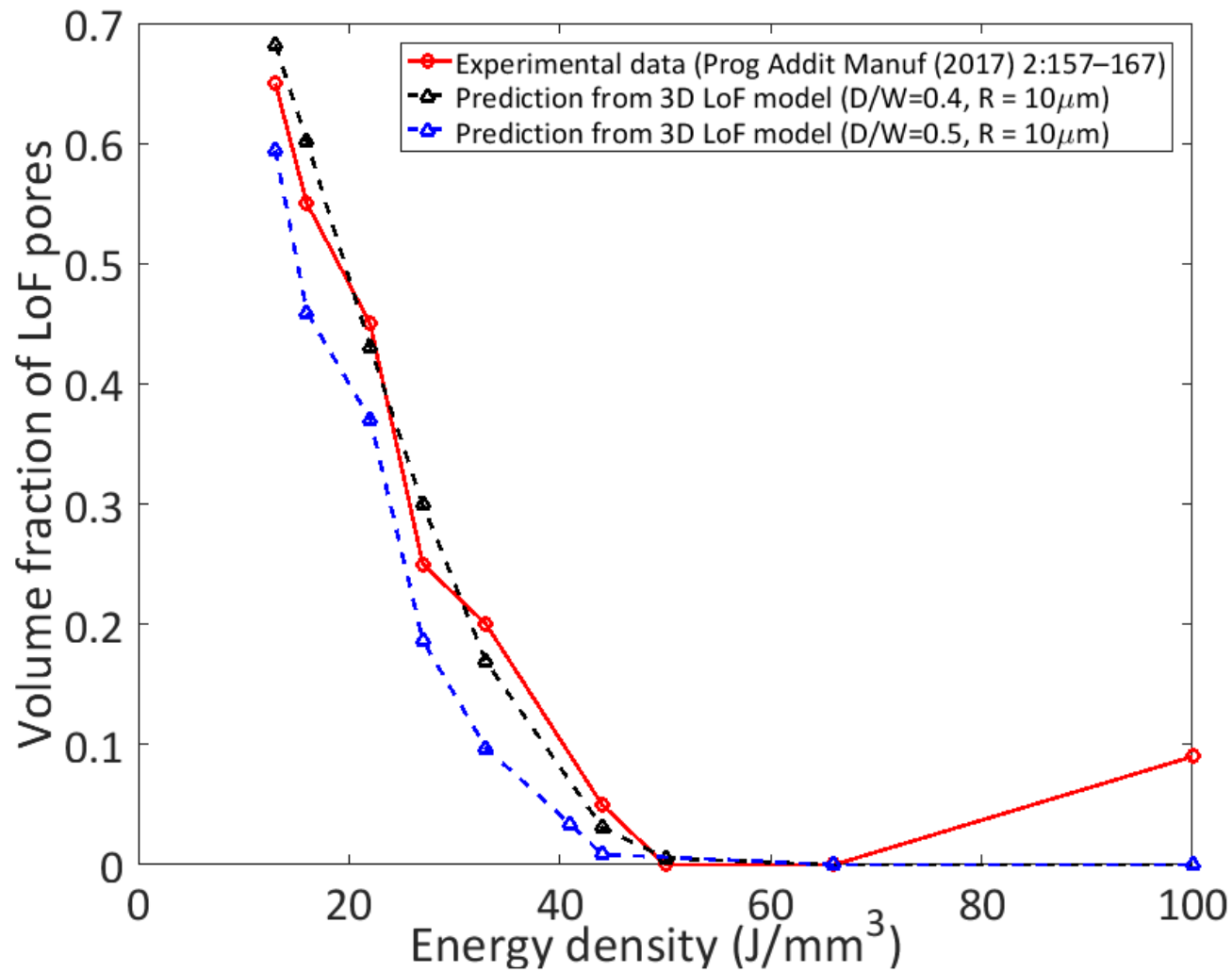
Influence of bead height, R



$$\text{Energy density} = \frac{P}{VHL}$$

P = laser power, V = laser velocity
H = hatch spacing, L = layer thickness

Influence of depth-to-width ratio, D/W



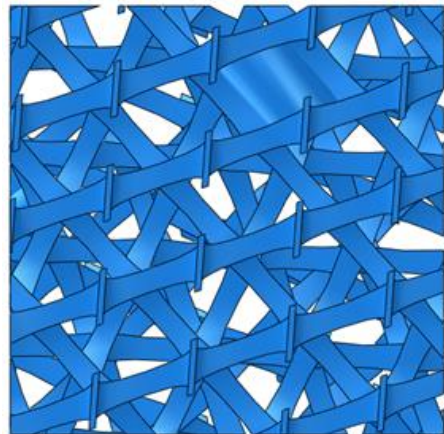
$$\text{Energy density} = \frac{P}{VHL}$$

P = laser power, V = laser velocity
H = hatch spacing, L = layer thickness

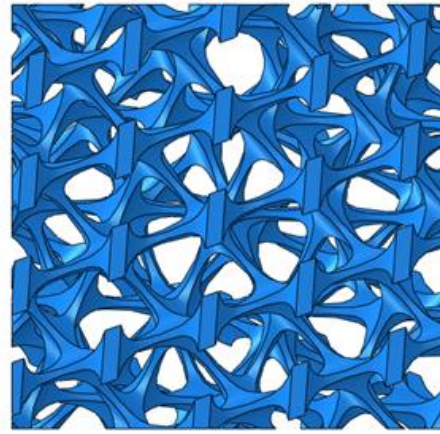
Influence of bead height, R

Material is Ti64, $P = 80$ W, $V = 1$ m/s, $L = 30\mu\text{m}$

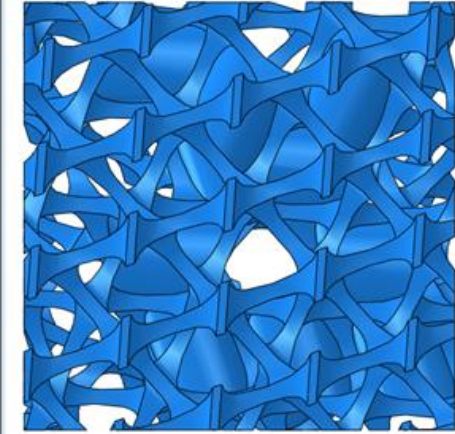
$H = 100\mu\text{m}$



$R = 10\mu\text{m}$
porosity = 7.85%

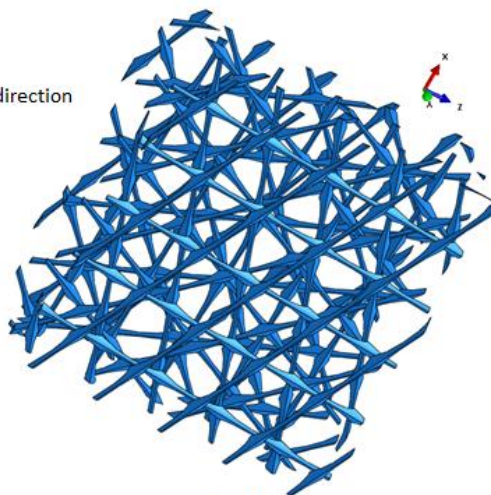


$R = 30\mu\text{m}$
porosity = 6.65%



$R = 40\mu\text{m}$
porosity = 8.79%

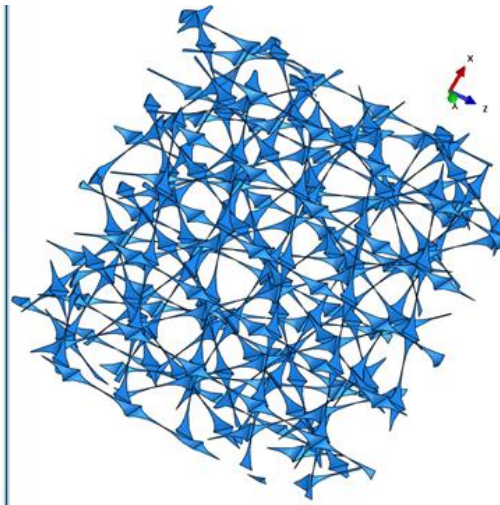
Y = build direction



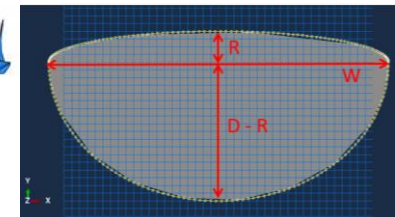
$R = 10\mu\text{m}$
Porosity = 1.06%



Y = build direction

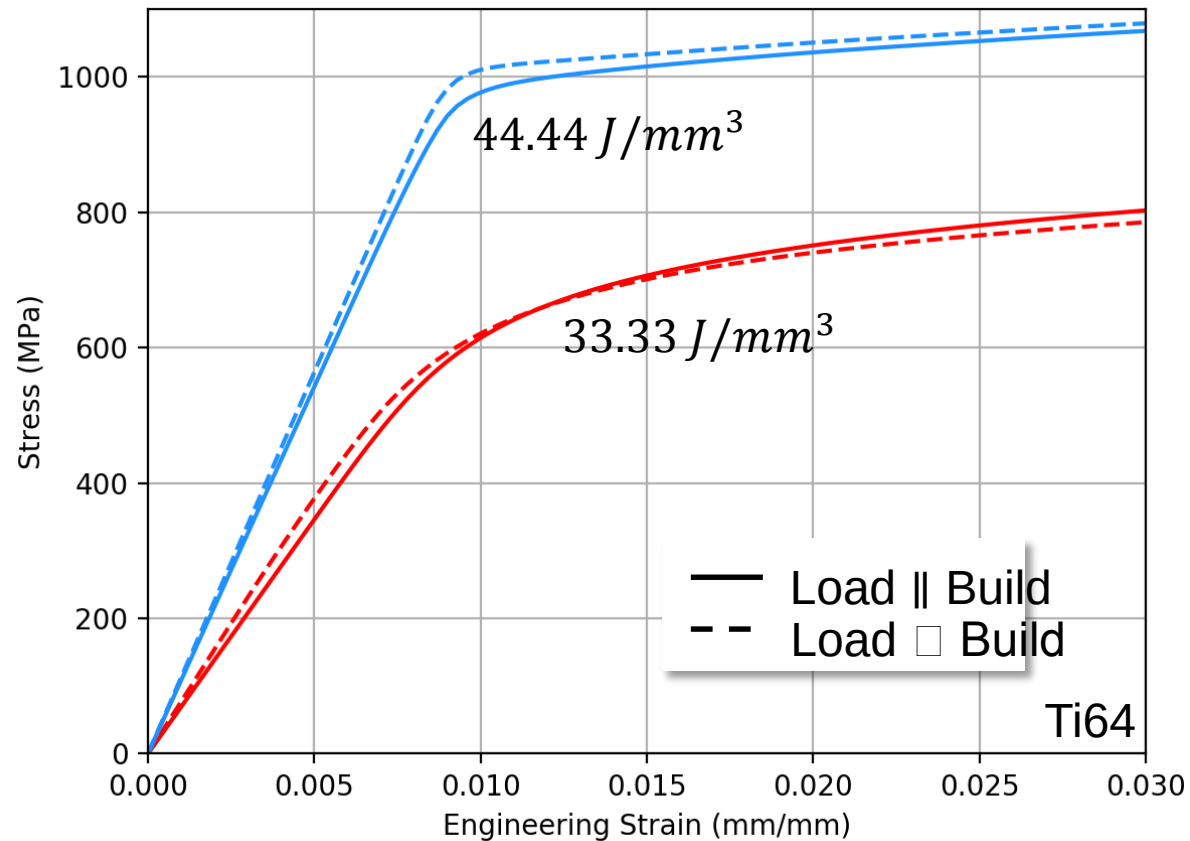


$R = 30\mu\text{m}$
Porosity = 0.626%



$H = 85\mu\text{m}$

Directionality



Strain Localizations in the Vicinity of Explicitly Inserted 3D LoF pores

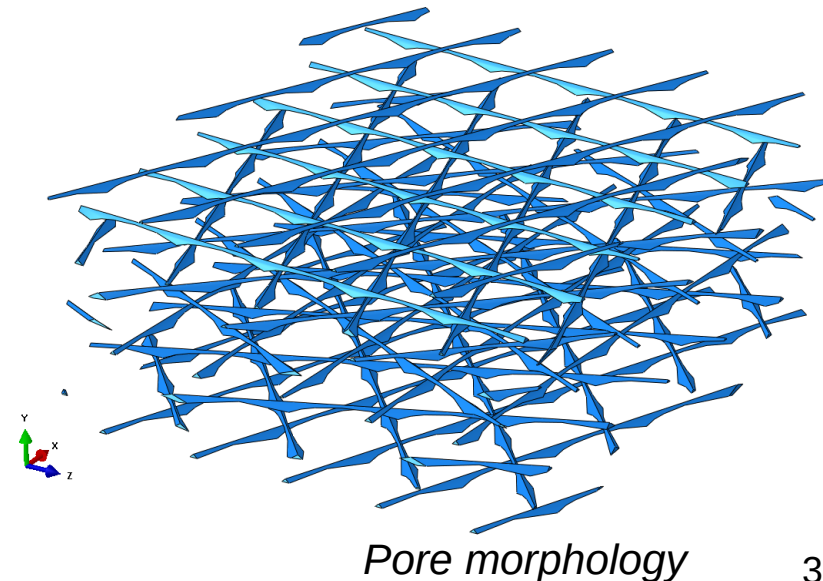
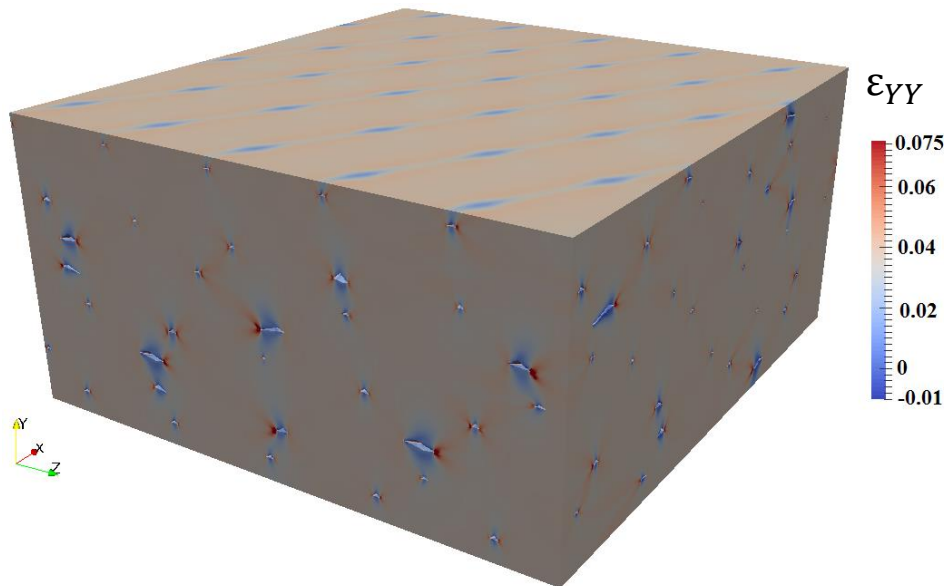


Material/Process related assumptions:

- Material assumed: Ti64, to align the efforts with TTT
- Process parameters: $P = 150$ W, $V = 1$ m/s, $H = 100$ μm , $L = 30$ μm , $\theta = 67$ degrees
- Porosity volume fraction $\sim 0.55\%$

Finite element modeling:

- 3D RVE with explicit LoF pores is meshed
- Only elastic properties are assigned to the RVE. Plasticity will be included in future studies.
- Bottom face fully fixed. Displacement controlled loading is applied in the build direction, YY



Pore morphology

Characterizing Porosity in 3D



- Descriptive Statistics
 - void volume fraction
 - mean pore diameter
 - with grains, we typically calculate sphere-equivalent diameter
 - alternatively, we can fit ellipsoid to each pore
- Distributions
 - Ω_3
 - aspect ratio
 - orientation
 - nearest-neighbor
- Multi-Dimensional Measures
 - 2-point spatial correlations
 - chord length distribution

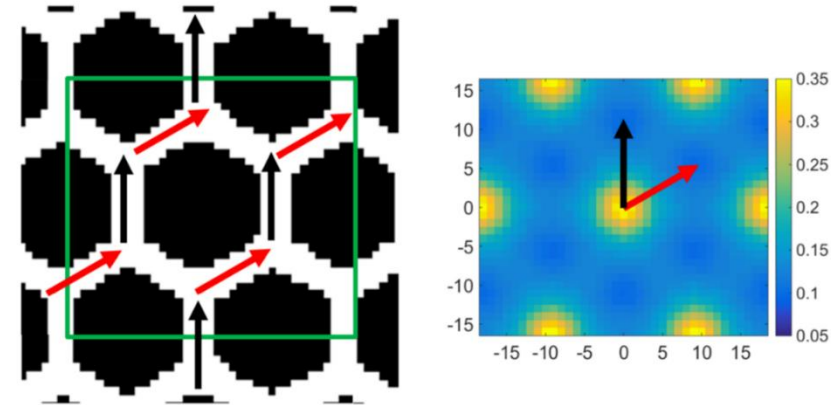


Fig. 2 Illustration of the computation and visualization of 2-point statistics while invoking the periodicity assumption. *Left:* the microstructure used in the computation. The actual microstructure, shown in the green box in the center, is extended by invoking the periodicity assumption. This extension is only for visualization purposes and allows us to see the use of the exact same sampling size for all vectors of interest in the microstructure domain. *Right:* the corresponding white-white autocorrelation map

Cecen et al. (IMMI, 2016)

Porosity Characterization: 2-point Statistics



- Preliminary results
- Process parameters:
 $P = 150 \text{ W}$, $V = 1 \text{ m/s}$, $H = 100 \text{ }\mu\text{m}$,
 $L = 30 \text{ }\mu\text{m}$, $\theta = 67 \text{ degrees}$
- Material: Ti64

2D slice

*Corresponding 2-point
correlation map*

