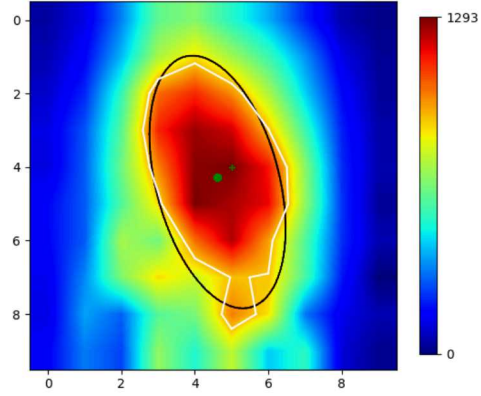
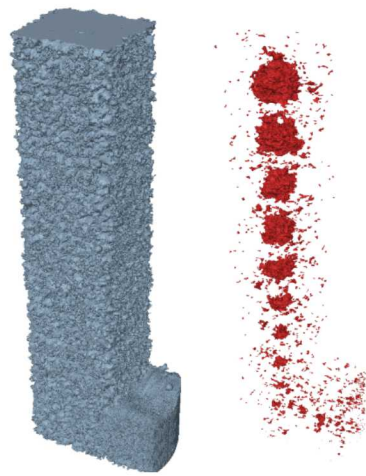


Correlation of Porosity Defects with In-situ Pyrometry in AM 316L SS



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September 30, 2019
Portland, OR

PRESENTED BY

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and B. Jared



Outline

AM Defect Detection

- Background
- Experimental Setup

In-situ pyrometry

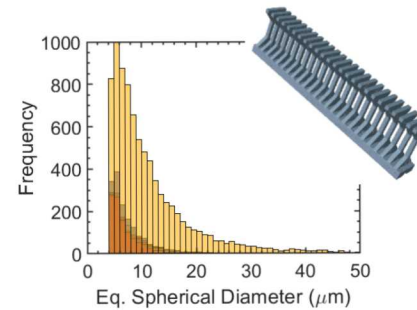
- Anomalous Melt Pool Identification

Multi-modal Registration

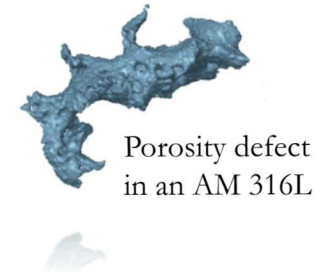
Spatial Coincidence of Melt Pools and Porosity

- Pore Detection Rates
- False Positives

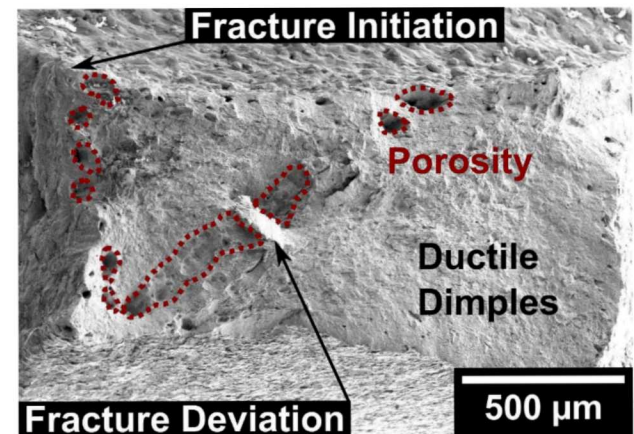
Summary



High-throughput tensile testing



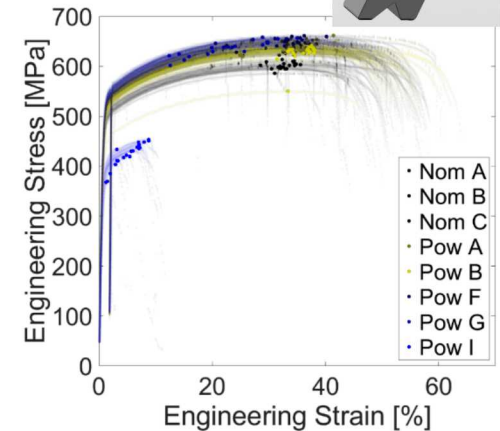
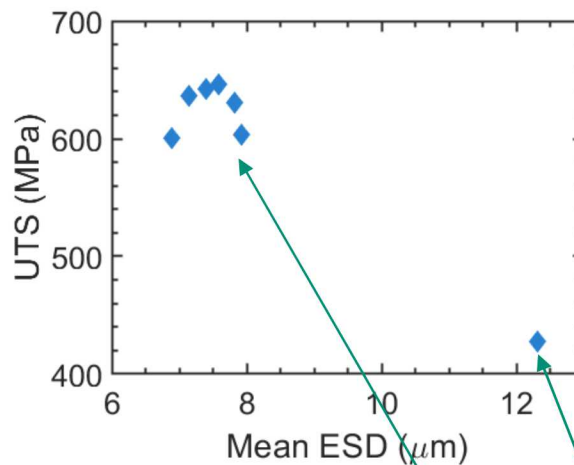
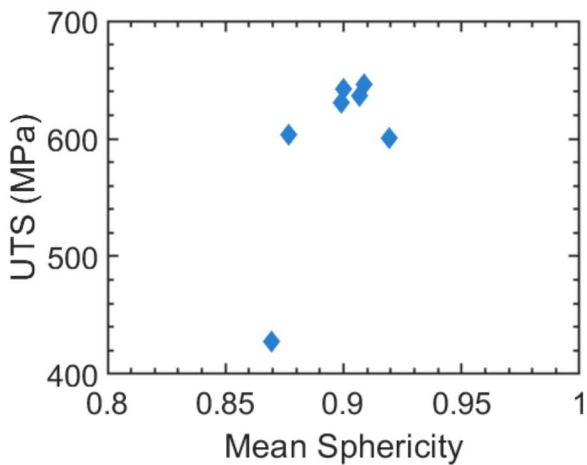
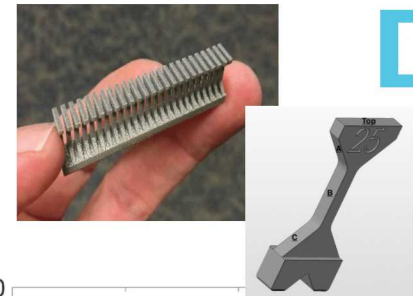
Porosity defect in an AM 316L



3 AM Defect Quantification Background

High variability in AM stainless steel

- Porosity defects can impact mechanical performance

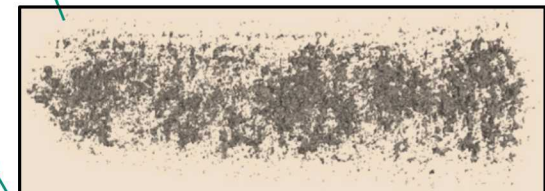


Nathan Heckman et al.

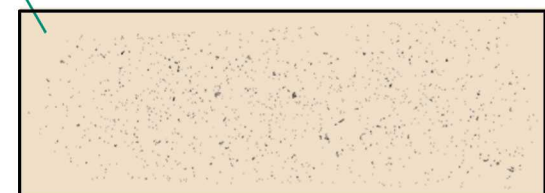
Wilson-Heid et al. found that UTS and elongation to failure affected when pore diameter reaches 16% and 9% of the cross-sectional area of fabricated cylinders

3D Porosity

Density



90%



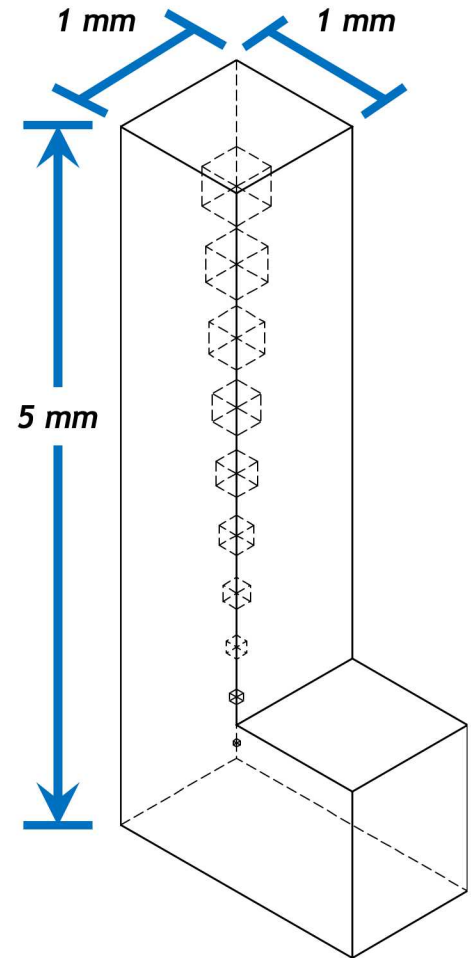
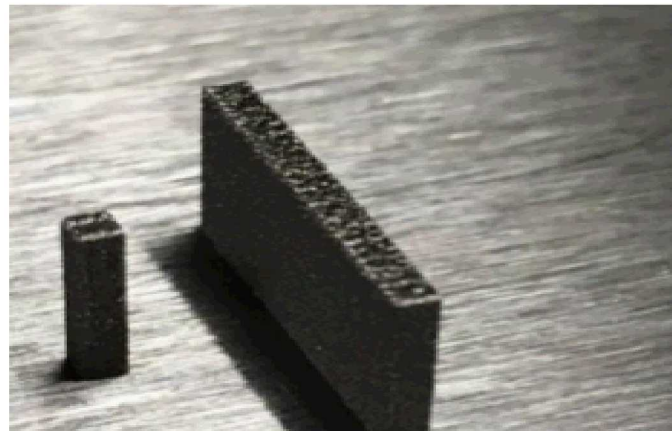
≥95%

Project Outline

- Recognize anomalous thermal signatures during an AM build using in-situ pyrometry and determine links to porosity defects identified ex-situ

Work Completed

- In-situ pyrometry during a laser-powder bed fusion (LPBF) build of 316L stainless steel
- Machine learning algorithms used to determine anomalous melt pools
- Porosity defects identified using post-build micro-CT
- **Identify minimum pore size detectable using pyrometry**
- **Identify correlations between pyrometry signal and unintentional porosity**



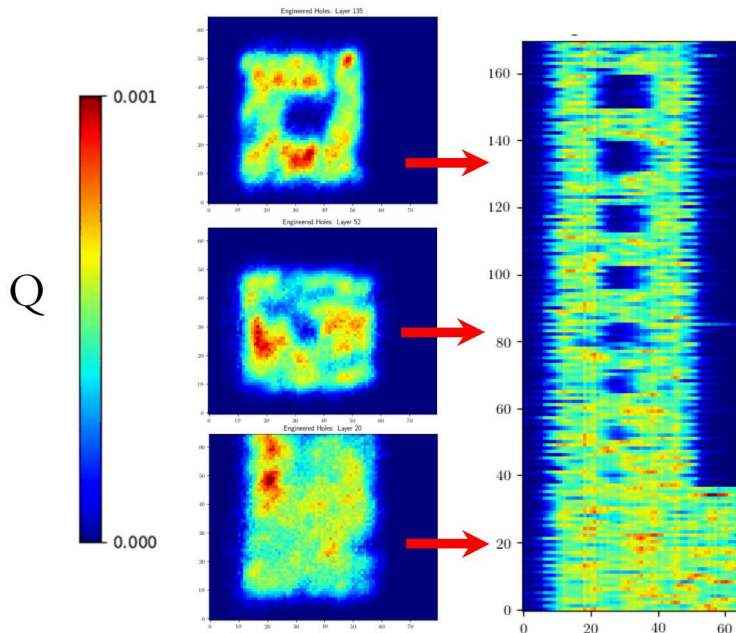
In-situ Pyrometry

Therma-Viz two-color pyrometer

- CMOS imagers, $\sim 20\mu\text{m}/\text{pixel}$
- 750 & 900nm filters (short & long)
- $T_{\text{pixel}} \cong \text{func}(I_1/I_2)$

Fixed field, angled side viewing

- FOV: 80 x 65 pixel (1.6 x 1.3mm)
- frame rate: 6-7kHz
- exposure: 90 μsec



THERMAL IMAGING



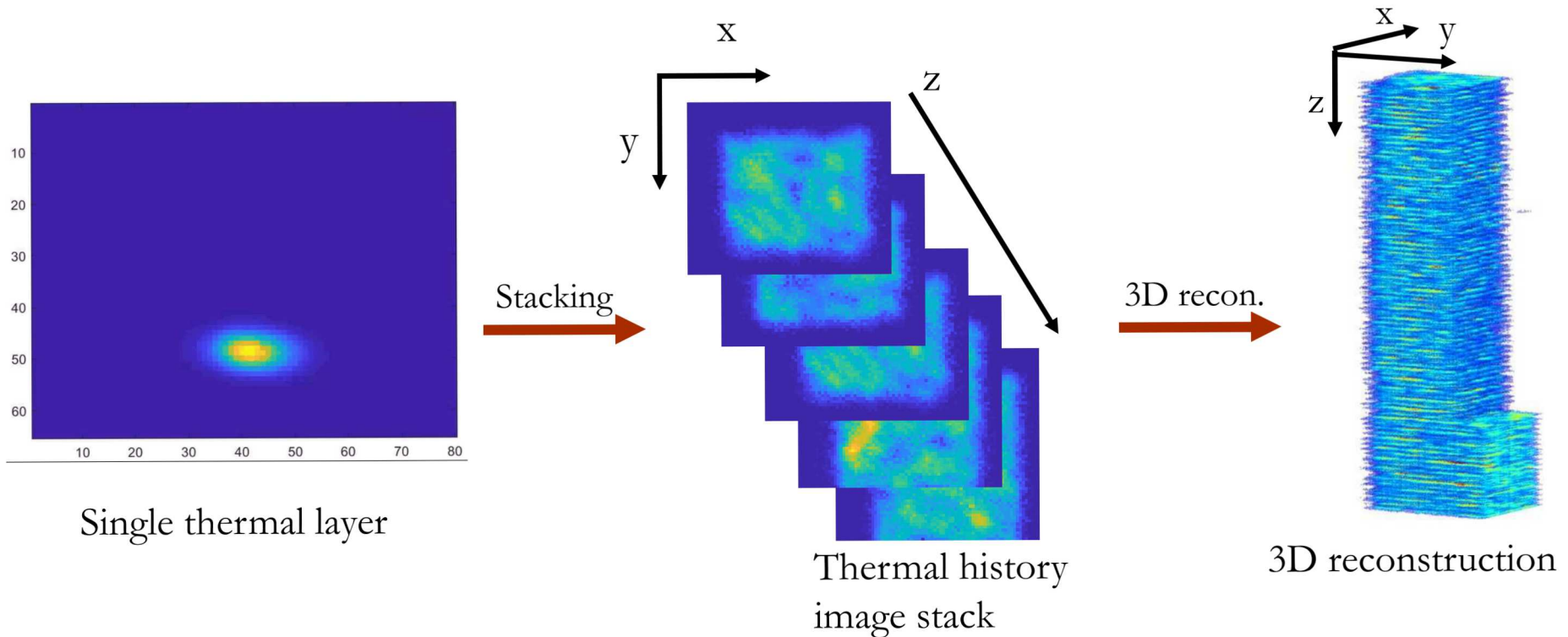
*Stratronics ThermaViz
2- color pyrometer
installed in ProX 200*



6 Thermal Imaging

Analyze pyrometer images for each build layer:

- 1) Identify and isolate melt pools in each thermal image
- 2) Subtract background intensity outside of the melt pool
- 3) Sum melt pool images for a build layer: **thermal history image**
- 4) 3D reconstruction of **thermal history images**

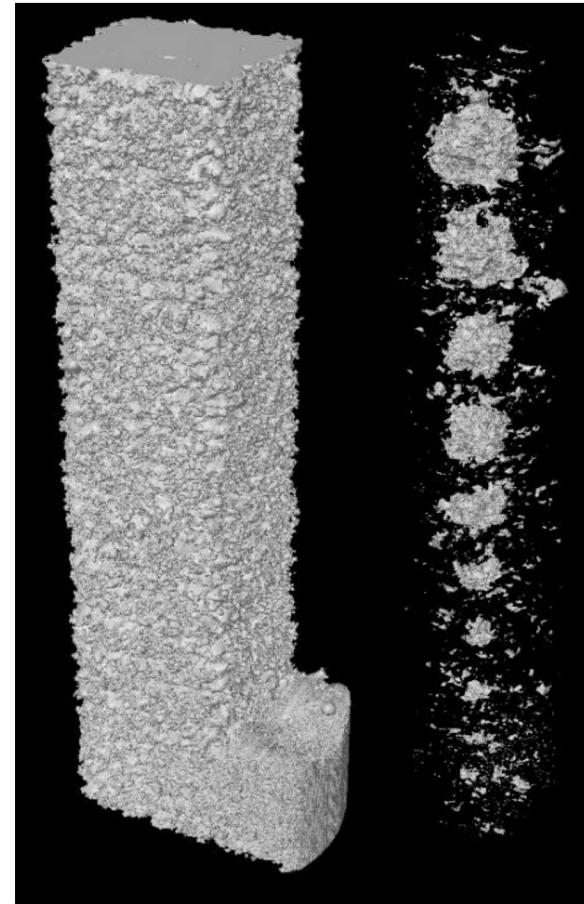


7 | Micro-Computed Tomography



Xradia 520 Versa

- 10 W, 140 kV
- Source-to-sample distance : 11.1 mm
- Cubic voxel size of 1.98 μm



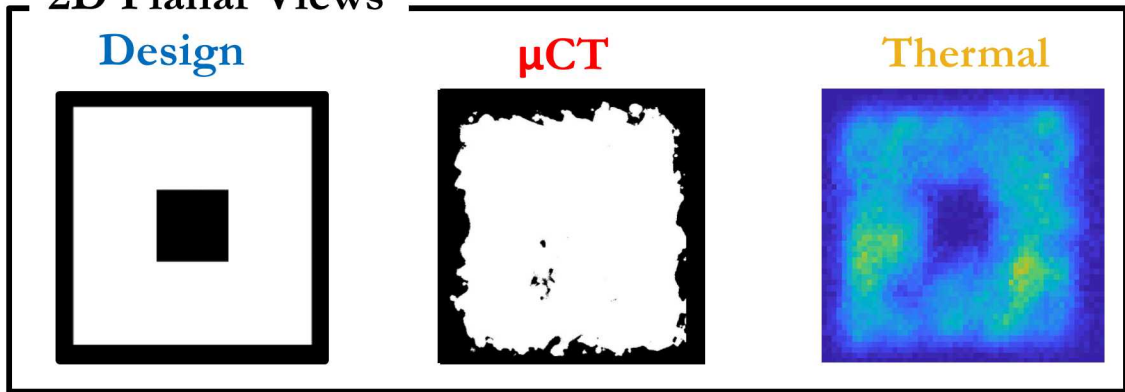
1 mm

Fly-through
video

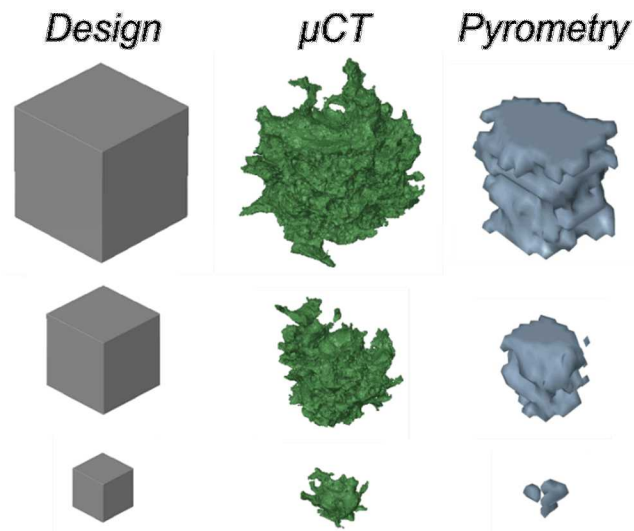
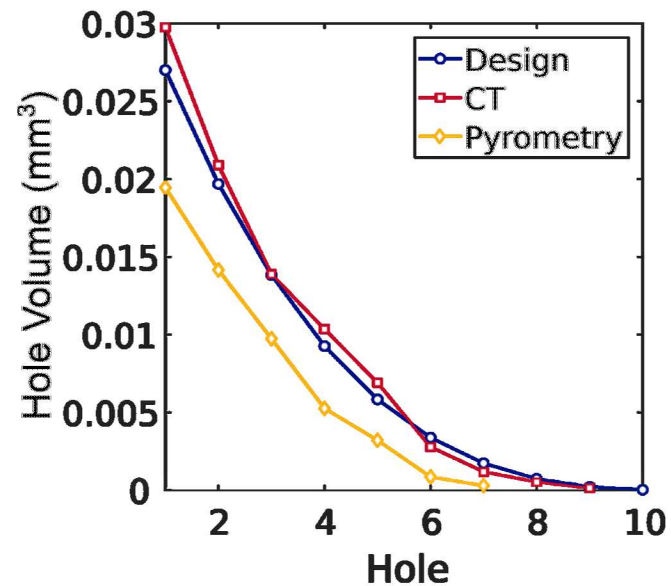
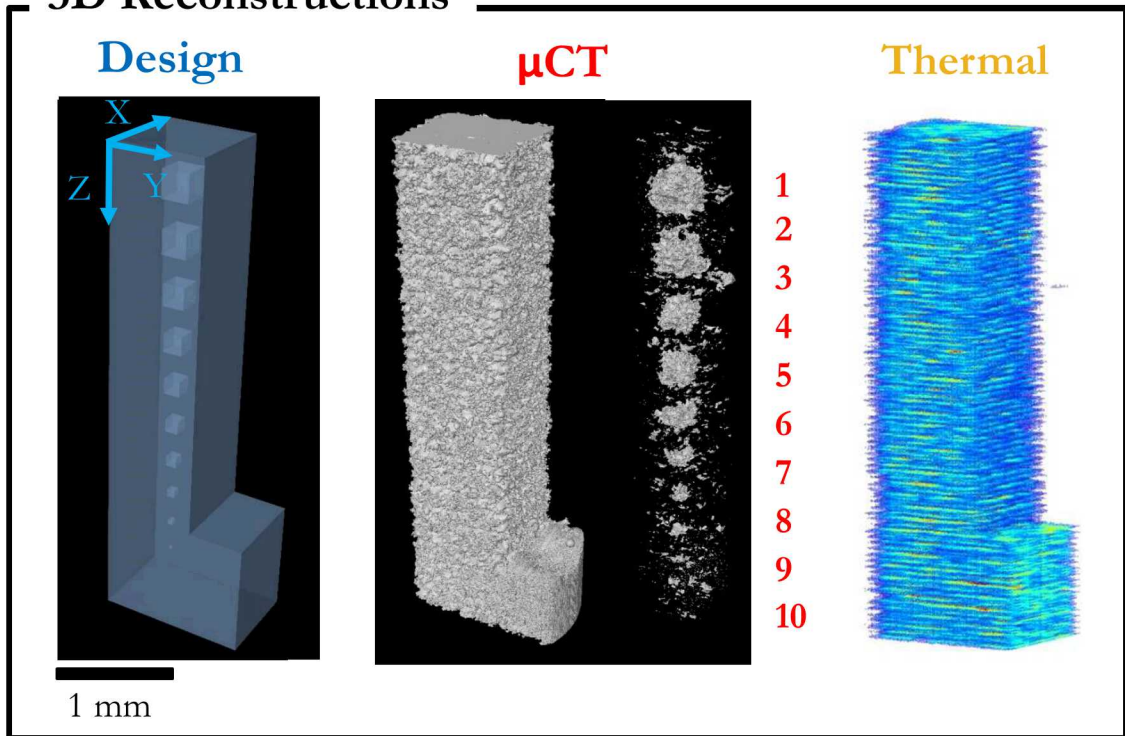


8 Minimum Detectable Feature Size

2D Planar Views



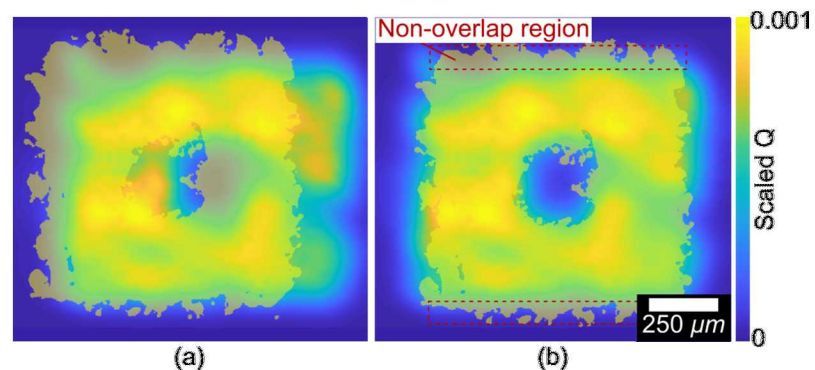
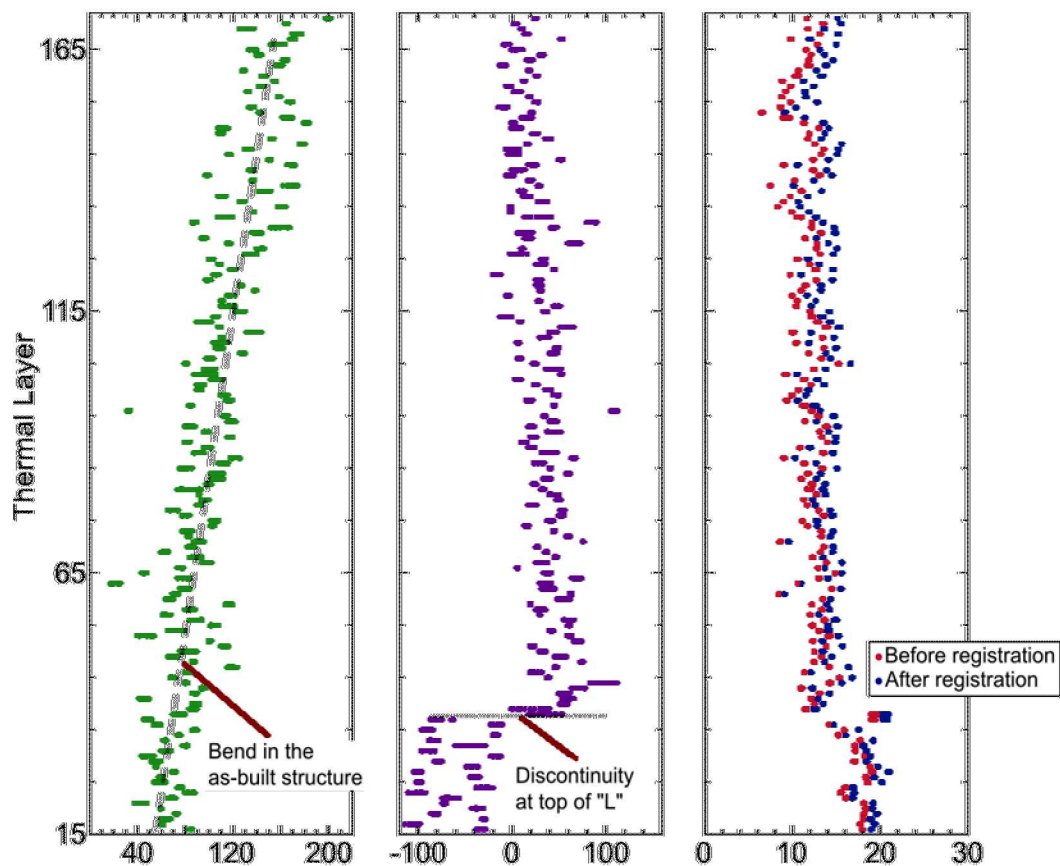
3D Reconstructions



9 Multi-modal Registration

Registration of in-situ pyrometry with post-build micro-CT; need to account for:

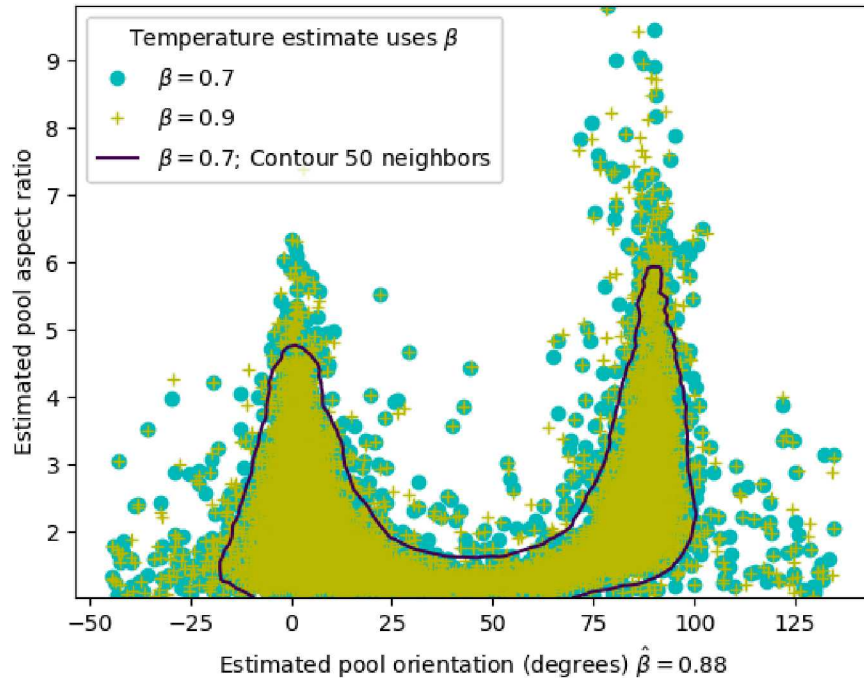
- Different spatial resolution
- Part distortions



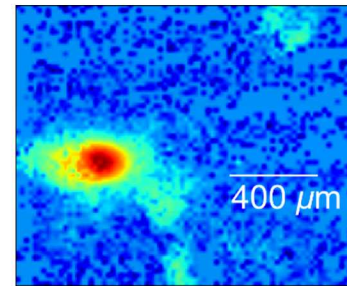
Registration assessed by overlap of high-intensity region with micro-CT data

- Mutual information methods
- Account for part distortions

Registration uncertainty between 1 to 3 pixels (up to 60 μm).

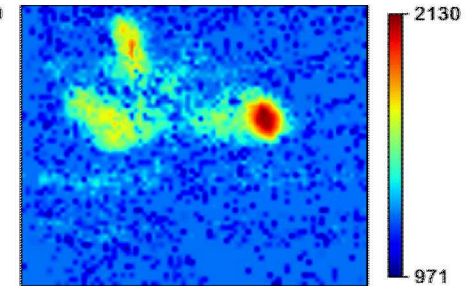


Normal

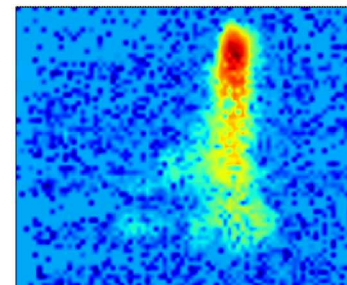


(a)

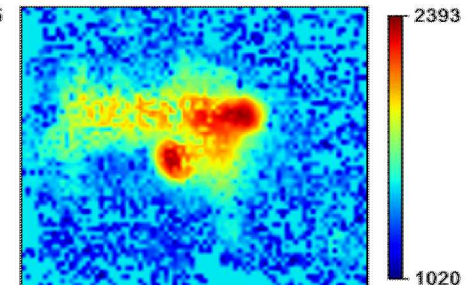
Outlier



(b)



(d)



(e)

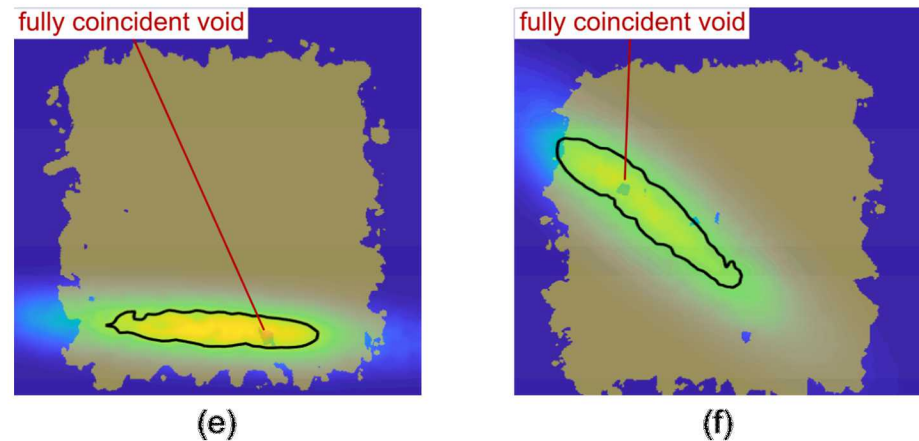
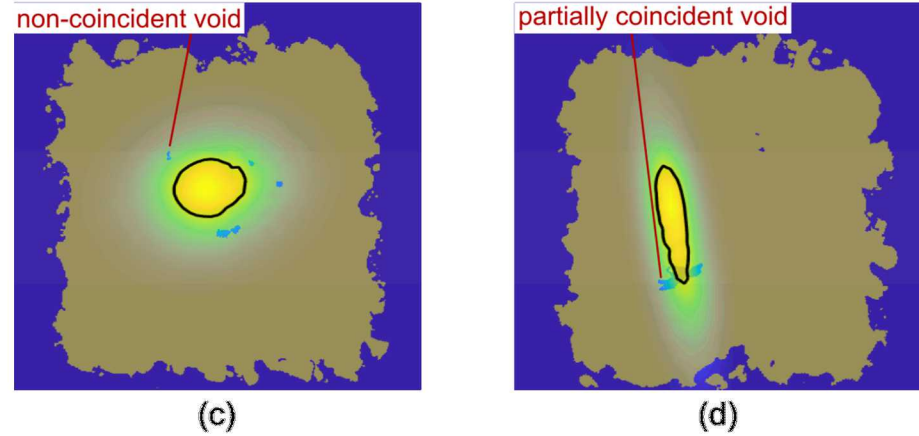
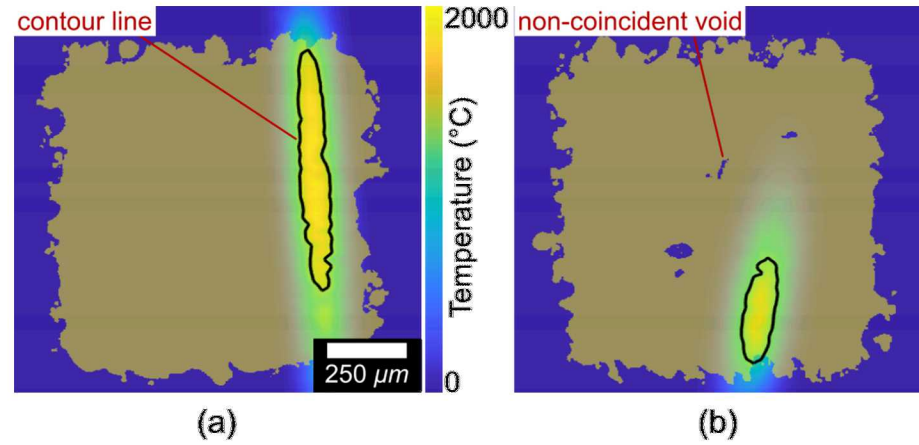
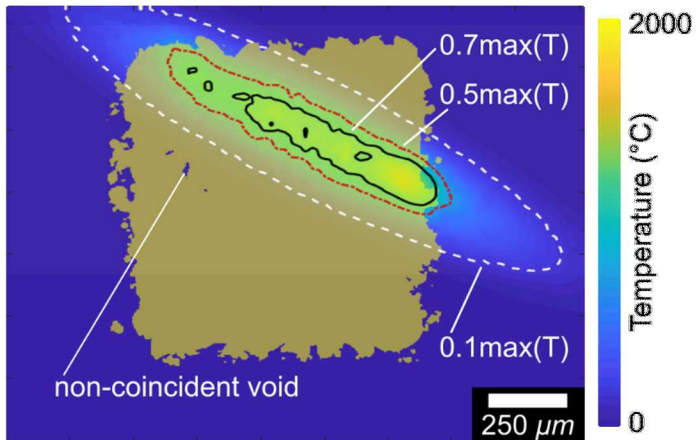
Anomalous melt pools identified using aspect ratios and pool orientations. Melt pools with few neighbors (outside the black contour line) deemed outliers.

Spatial Coincidence

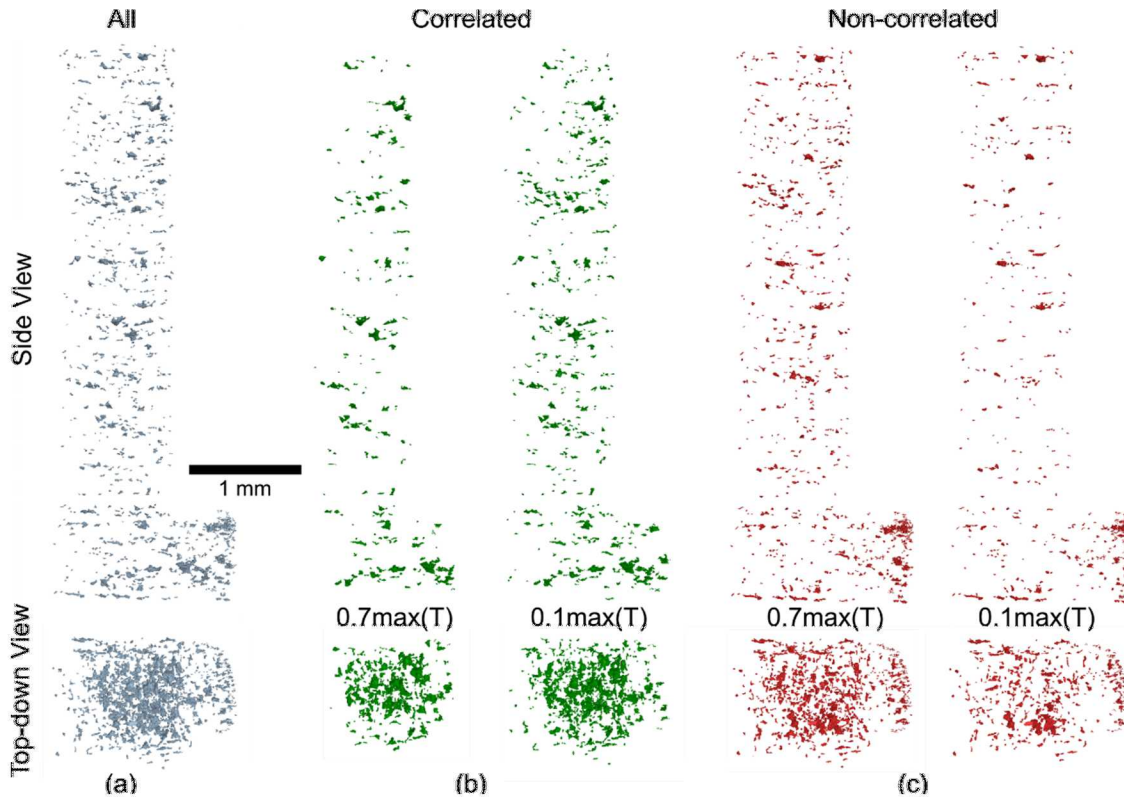
Three types of overlays:

1. Non-coincident
2. Partially coincident
3. Fully coincident

Different contour levels can be used to define coincidence



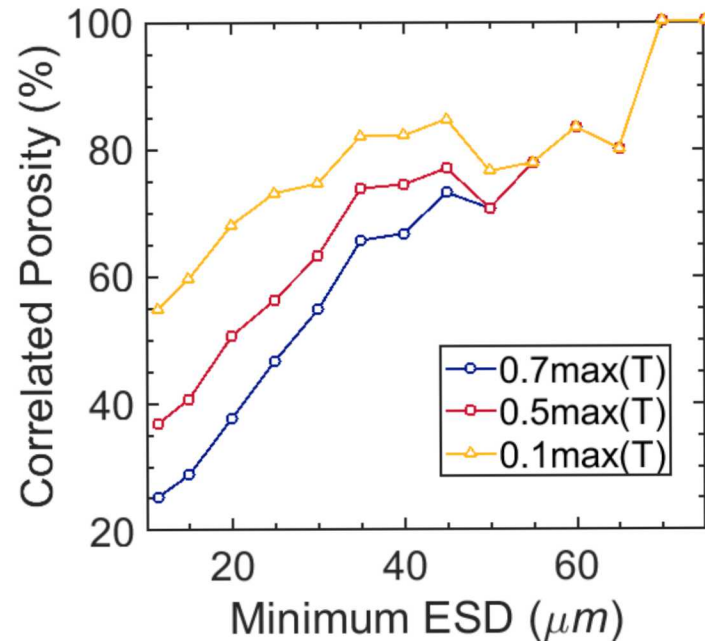
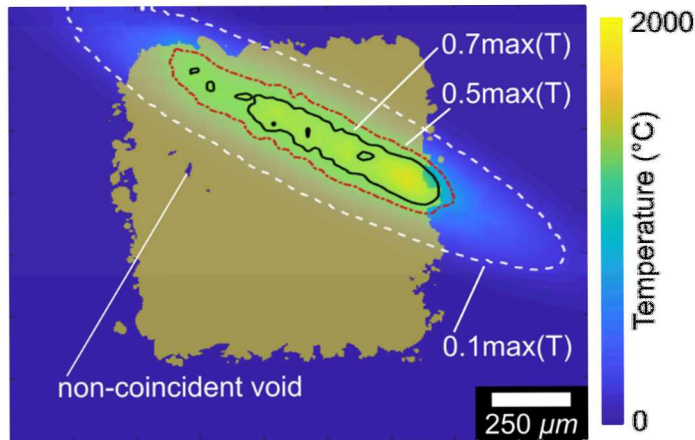
Visualization of pores correlated with outlier melt pools



Larger pores linked to outlier melt pools more often than smaller pores

Minimum ESD (μm)	11.4	20	30	40	50	60	70
Thresh $0.1T_p$	55%	68%	75%	82%	77%	83%	100%
Thresh $0.5T_p$	37%	51%	63%	74%	71%	83%	100%
Thresh $0.7T_p$	25%	38%	55%	67%	71%	83%	100%
Total # Pores	966	310	106	39	17	6	2

Spatial Coincidence

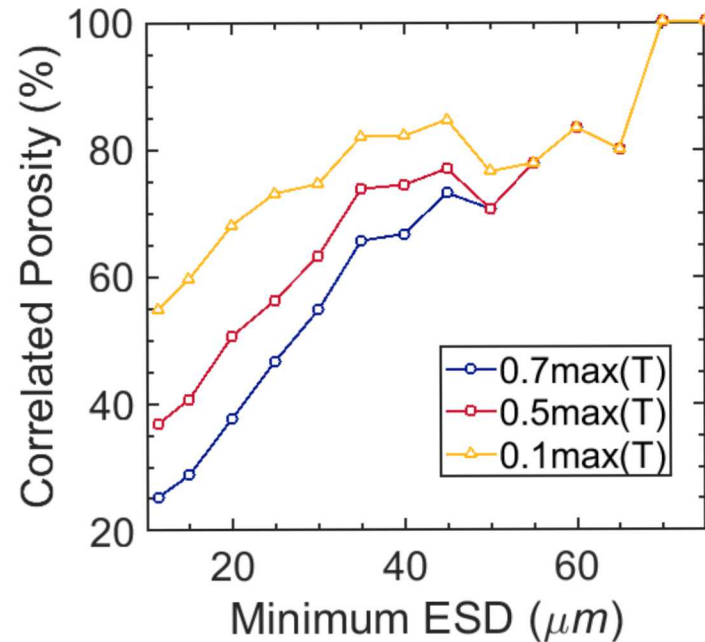
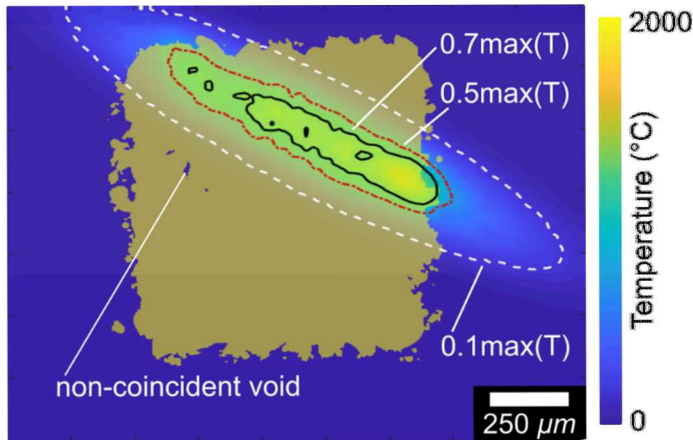


Larger pores linked to outlier melt pools more often than smaller pores

False positives: melt pools identified as abnormal that are not spatially coincident with any identified pores.

	False positive melt pools	Coincident melt pools	False positive rate
Thresh $0.1T_p$	105	352	23%
Thresh $0.5T_p$	204	253	45%
Thresh $0.7T_p$	265	192	58%

Spatial Coincidence



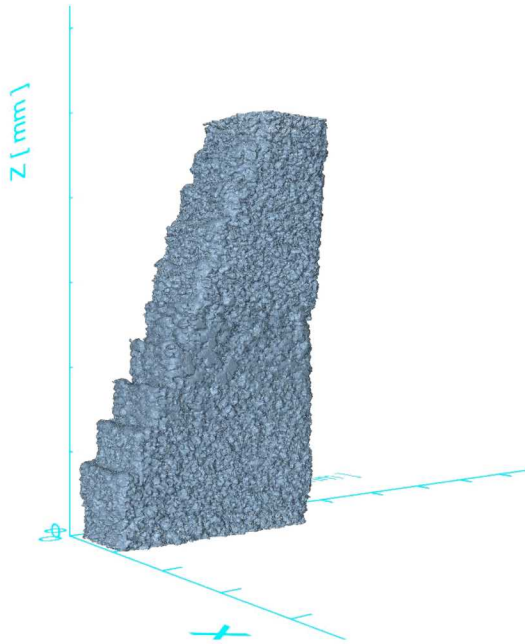
Larger pores linked to outlier melt pools more often than smaller pores

Abnormal melt pools reliably predict enhanced pore quantity at a much higher rate than normal melt pools or simply selecting melt pools at random

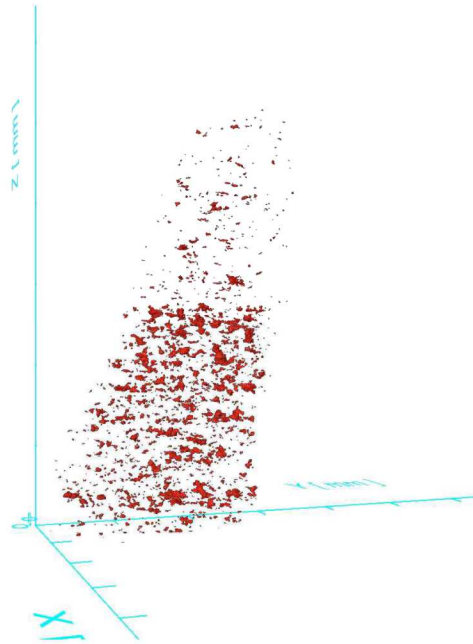
	All Melt Pools (10,597)		<i>Outlier</i> Melt Pools (457)	
	Correlated Pores	Detection Rate	Correlated Pores	Detection Rate
Thresh $0.1T_p$	580 (94%)	0.06	529 (55%)	1.20
Thresh $0.5T_p$	576 (93%)	0.05	356 (37%)	0.78
Thresh $0.7T_p$	560 (91%)	0.05	245 (25%)	0.53

Staircase shaped structures

Process parameters (velocity, power and hatch spacing) varied along build height



Materials



Pores

Volumetric assessments of complex AM build geometries may not be sufficient to determine as-built adherence to design constraints

- Shape factors and surface topology expose deviations a volumetric analysis cannot

Abnormal melt pools can be defined by simple shape and orientation measures, observed by in-situ pyrometry.

Abnormal melt pools correlate to increased amounts of pore content in the as-built structure with an accuracy of 77% for voids having an ESD of at least 30um

Abnormal melt pools reliably predict enhanced pore quantity at a much higher rate than normal melt pools or simply selecting melt pools at random



Questions



Defect Detection in AM 316L SS

Project outline and why it is important

- Laser powder bed fusion (LPBF) provides production and design agility
- In-situ monitoring allows builds to be assessed in real-time, potentially saving time, material, and cost
- Porosity can introduce variability and detection in-situ can save time and money
- Variability in mechanical performance makes qualification of material challenging

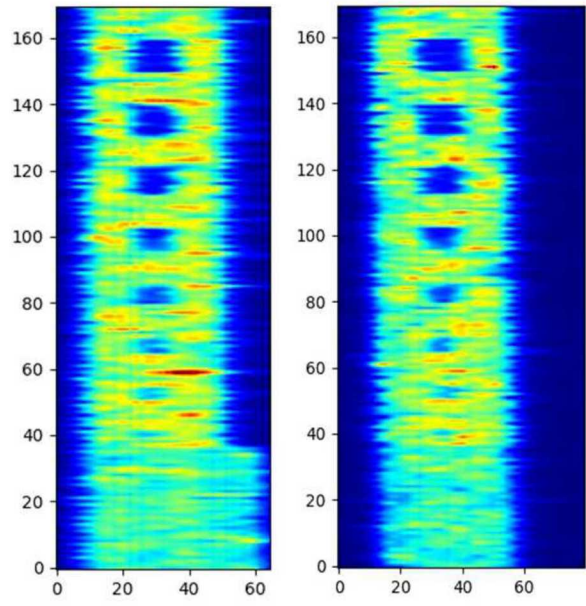
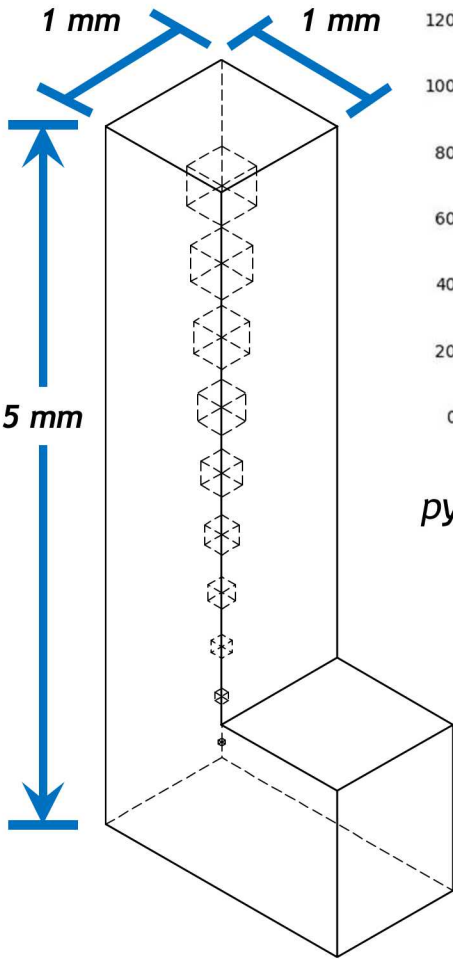
Project goals

- Identify minimum pore size detectable using pyrometry
- Identify correlations between pyrometry signals and unintentional porosity

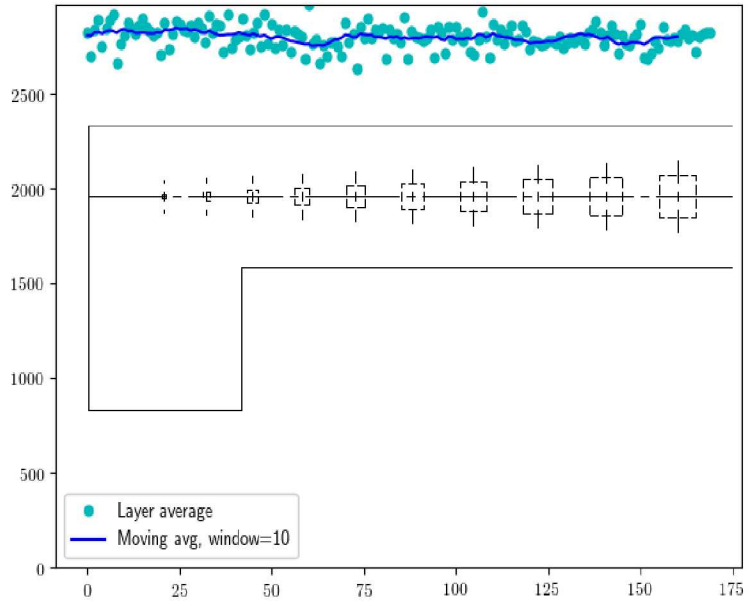
Work completed toward those goals

Table 3: Porosity detection rates: pores correlated per image. Data shown for all 10,597 melt pools (*normal* and *outliers*) and exclusively for the 457 *outlier* melt pools for different temperature contour values. T_p is the maximum temperature in each melt pool image.

	All Melt Pools (10,597)		<i>Outlier</i> Melt Pools (457)	
	Correlated Pores	Detection Rate	Correlated Pores	Detection Rate
Thresh $0.1T_p$	580 (94%)	0.06	529 (55%)	1.20
Thresh $0.5T_p$	576 (93%)	0.05	356 (37%)	0.78
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pyrometer data, YZ section (left) & XZ section (right)



average peak temperature per build layer

Internal cavity design - (316L Stainless Steel)

