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High Value Pyrometry-To-Defect Correspondence in Laser Powder Bed Fusion of 316L Stainless Steel

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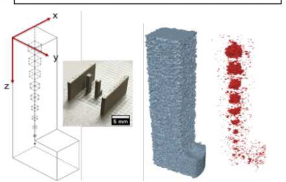
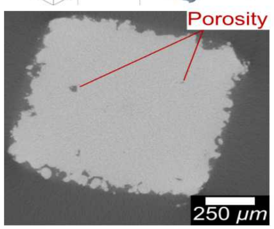
ABSTRACT

Fundamental questions regarding the intrinsic reliability of additively manufactured (AM) metals is a remaining challenge to the approval and qualification of AM metal in engineered components. One thread being pursued to address this challenge is the detection of defect "signatures" in the AM process. Reliable detection of these features may inform real-time modification to processing conditions if observed *in-situ* or lot acceptance decisions if observed post-build. Here, *in-situ* pyrometry data acquired during the AM process is shown to provide exceptional correlation temporally and spatially with defects observed via post-build micro-computed tomography. Accuracies in these correlations measure 71% or greater for pores having equivalent spherical diameters of at least 50 μm.

EXPERIMENTAL

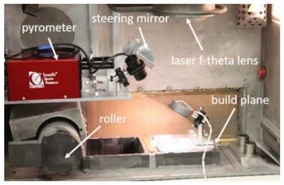




Using a 3D Systems Pro X DMP 200, an "L-column" geometry was printed from 316L stainless steel powder having intentional 1) internal cavities of prescribed size and 2) intermittent porosity throughout. Laser power was fixed at 103W, with a beam diameter of 100um, a nominal powder layer of 30um, hatch spacing of 50um, and a build velocity of 1.4 m/s.

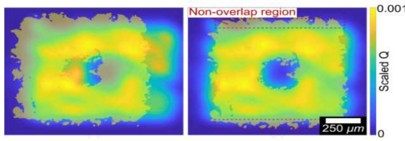
Radiance measurements were acquired with a Stratonics two-color pyrometer located within the build chamber as shown at right. The pyrometer contains two silicon CMOS cameras (MV1-D1024E from Photon Focus) that receive emitted light at 750nm and 900nm, respectively, via 50 nm bandpass filters. The camera FOV was 65 x 80 pixels with a resolution of 21 pixels. Accurate timing between machine and cameras was achieved using a TTL trigger from the Pro X at the beginning of each build layer. Raw camera images were taken using a 90s exposure at a rate of 6-7 kHz using he Stratonics burst mode and saved to disk. In this way, estimation of absolute temperature is possible without detailed knowledge of emissivity[1].

Micro-computed tomography was then performed, post-build on the as-built structure using a ZEISS Xradia 520 Versa at a power of 10W and 140 kV. A source-to-sample distance of approximately 11.1 mm was used with a magnification factor of 4 to produce a cubic voxel size of 1.98 um per voxel edge throughout the dataset. Segmentation was performed in a manner similar to approaches previously discussed[2] using a combination of custom scripts developed in MATLAB and FIJI to discriminate between solidified metal and internal porosity.



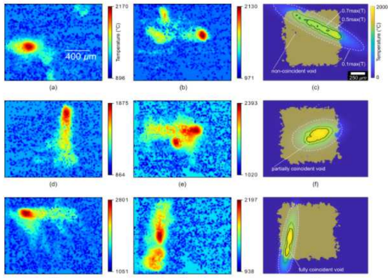
1. D. J. Dagel, et al. *.Four-color Imaging Pyrometer for Mapping Temperatures of Laser-Based Metal Processes*. ***Proceedings of SPIE***, *vol. 986103 : pp. 1-8, 2016.*
2. J. D. Madison, et al., *Corroborating Tomographic Defect Metrics With Mechanical Response in an Additively Manufactured Precipitation-Hardened Stainless Steel.* ***AIP Conference Proceedings, of the 44th Annual Rev. of Progress in Quantitative Non-Destructive Evaluation***, *vol. 37: pp. 1-8, 2018.*
3. E. B. Gulsoy, et al., *Application of Joint Histogram and Mutual Information to Registration and Data Fusion Problems in Serial Sectioning Microstructure Studies.* ***Scripta Materialia***, *vol. 60 (6) : pp. 381–384, 2018.*

REGISTRATION & ALIGNMENT



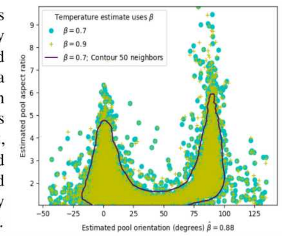
Pyrometry and micro-CT data were then spatially registered to one another prior to calculating correlative statistics. It was necessary to optimize registration to calculate voxel-to-voxel correlations and to account for differing spatial resolutions between pyrometry and micro-CT data. Registration was completed by applying translations via mutual information methods to micro-CT data along the X, Y and Z axes to maximize coincidence with thermal history (Q) at each build layer. Rotations were forbidden during each step of the registration process. Z translation occurred first by manually aligning the top and bottom surfaces of the intentionally fabricated cavities in the as-built structure as identified by Q and segmented micro-CT data. Next, translations, within the X-Y plane, were completed layer-by-layer using mutual information methods[3] to optimize overlap between sample geometry, surface roughness and intentionally fabricated cavities between Q and segmented micro-CT layers.

OUTLIER IDENTIFICATION



Temperature estimates for normal and outlier melt pools are shown above in the left and middle columns. The corresponding best fit ellipses for each are presented in the right column overlaid atop corresponding micro-CT layers.

Melt pool images classified as "normal" were overwhelmingly characterized by a single connected region of elevated temperature with a distinct shape and tail wherein the direction of travel is unambiguous. In contrast, "outlier" images often contained disconnected regions of elevated temperature spread asymmetrically and are often related to spatter events.



Correlation statistics reveal for pores having an equivalent spherical distance (ESD) of at least 30um, 40um, and 50um, coincidence with an "outlier" pyrometry signal exist at frequencies of at least 55%, 67% or 71%, respectively for the meltpool thresholds considered $(0.1T_p, 0.5T_p, 0.7T_p)$ and illustrated above.

Mininum 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

This work is in peer review for publication in an archival journal

CONCLUSION

Increased porosity in LPBF AM can be directly linked to in-situ pyrometry data. This work goes beyond estimating average build porosity and predicts spatial locations for enhanced porosity using outlier melt pool signatures. The data and approach presented here are, to the authors' best knowledge, the first quantitative demonstration of a direct correlation between anomalous thermal signatures during a LPBF build and unintentional porosity presence in AM 316L.