Joint Special Interest Group meeting between euspen and ASPE
Advancing Precision in Additive Manufacturing
TU Berlin, Germany, October 2025
www.euspen.eu

Improving X-ray CT porosity analysis towards enhanced in-situ monitoring and real-time defect prediction in metal laser powder bed fusion

N. Bonato[1], F. Zanini[1], S. Carmignato[1]

[1]*Department of Management and Engineering, University of Padova, Vicenza, Italy*

nicolo.bonato@unipd.it

Abstract

Laser powder bed fusion of metals enables the fabrication of complex components but is prone to defects such as porosities, which can compromise part integrity. This study investigates a novel reference object designed to enhance the traceability of porosity measurements via X-ray computed tomography. A data fusion strategy combining optical profilometry and computed tomography was implemented to calibrate defects resembling typical PBF-LB/M porosities. A new segmentation method, named advanced local-adaptive, demonstrated improved accuracy over existing algorithms. This approach enables the generation of reliable porosity reference data to support the development of advanced methodologies for in-process monitoring and real-time defect size prediction.

Laser powder bed fusion; X-ray computed tomography; Porosity traceability; Porosity segmentation; In-process monitoring

1. Introduction

Laser powder bed fusion of metals (PBF-LB/M) has rapidly advanced in recent years, driven by its capability to fabricate complex geometries with high mechanical performance. However, the intricate process dynamics often lead to internal defects, particularly internal porosities, that can critically compromise part integrity [1]. Accurate characterization of such defects is therefore essential not only for part qualification but also as feedback for process optimization.

X-ray computed tomography (CT) is widely adopted for inspecting complex components and detecting internal features, offering quantitative information on pore size, morphology, and spatial distribution [2]. Nonetheless, ensuring metrological traceability in CT-based porosity measurements remains a significant challenge. The lack of standardized procedures, coupled with the irregular shapes and surface textures of PBF-LB/M pores [3], further complicates the attainment of accurate dimensional measurements and evaluation of task-specific uncertainties. This limits the reliability of CT porosity measurements for quality assurance.

A notable effort to address these limitations is presented in [4], where a reference object with calibrated hemispherical pores was introduced to verify systematic CT errors and estimate measurement uncertainty. However, such regular geometries do not adequately reflect complex and irregular shapes typical of PBF-LB/M porosities [5].

This work investigates a novel reference object, specifically designed considering PBF-LB/M process and related defects [6]. A data fusion strategy was employed for the geometric calibration of internal voids. The reference object is used to assess the accuracy of conventional porosity analysis algorithms and to support the development of advanced segmentation methods with improved measurement accuracy. These enhanced methods provide reliable labels for training machine learning models aimed at predicting defect occurrence and size directly from in-process monitoring data, thus enabling more robust and traceable PBF-LB/M monitoring solutions.

2. Materials and methods

The development of the reference object for PBF-LB/M porosity measurements considered both manufacturing constraints and the measurement requirements for geometric calibration of artificial defects. Three main defect types were identified and included in the object: lack-of-fusion (LoF), keyhole, and spatter-related porosities of varying sizes. To enable access for calibration, the defects were positioned in the top region of a 5 mm diameter cylindrical sample (Fig. 1a).

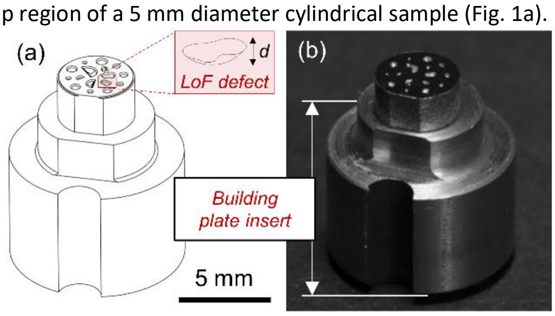

Figure 1. Design of the reference object featuring artificial defects [6], with the inset showing a defect resembling a lack-of-fusion pore (a); fabricated sample on the building plate insert, shown after milling the top surface (b).

Fabrication was carried out on a Sisma MYSINT100 PBF-LB/M machine. After printing, the sample's top surface was milled and polished to ensure planarity and a smooth surface. This enabled assembly with a polished cylindrical counterpart of same size, effectively sealing the open-top calottes to resemble realistic PBF-LB/M pores during subsequent CT scanning. Fig. 1b shows the fabricated sample after milling. The sample was built on a removable building plate insert [7], to facilitate both post-processing and CT measurement.

For defect calibration, a data fusion approach was adopted, combining multi-view focus variation (FV) measurements with high-resolution CT data. A Sensofar S-Neox 3D optical profilometer in FV mode was used to acquire defect geometry as point cloud data. Multiple tilts of the sample during acquisition helped minimize shaded regions, common due to the free-form nature of the defects and the complex surface texture caused by sintered particles and spatter deposits. Residual shaded areas were acquired using local CT-derived point clouds obtained from CT scans at 3 µm voxel size with a Nikon Metrology MCT225 system.

Each complete point cloud was converted into a surface mesh, and the top surface was closed using a least-squares fitting plane, enabling to compute the volume of each defect. Systematic error correction and calibration uncertainty were determined by adapting the substitution method defined in ISO 15530-3 [8], using the calibrated sample proposed in [4] as reference.

The new reference object, after calibration, was employed in an experimental campaign to evaluate the measurement accuracy of commonly used CT porosity analysis algorithms implemented in the software VGSTUDIO MAX. Specifically, this study reports the performance of two algorithms: the only threshold (OT) method, which segments pores using a fixed grey-level threshold, and the easy pore (EP) method, which leverages local contrast differences between material and voids.

Moreover, part of the experiments was dedicated to the development of improved segmentation approaches.

The reference object was CT scanned again using the MCT225 system, at a voxel size of 4 µm, both in the presence and absence of entrapped powder particles within the artificial defects.

3. Results

Fig. 2 reports the mean absolute percentage deviation from the calibrated volumes for a subset of defects, based on repeated scans of the reference object. When defects were free from entrapped powder (Fig. 2a), deviations remained below 10% for both OT and EP, with reduced variability - except for the smallest pores. Under this condition, the reference object also enabled the development and validation of a novel porosity segmentation method: the advanced local-adaptive (ALA) approach. ALA considers both local contrast and grey value gradient information to determine pore boundaries. The method consistently outperformed OT and EP across all defect types and sizes, achieving lower deviations and variability.

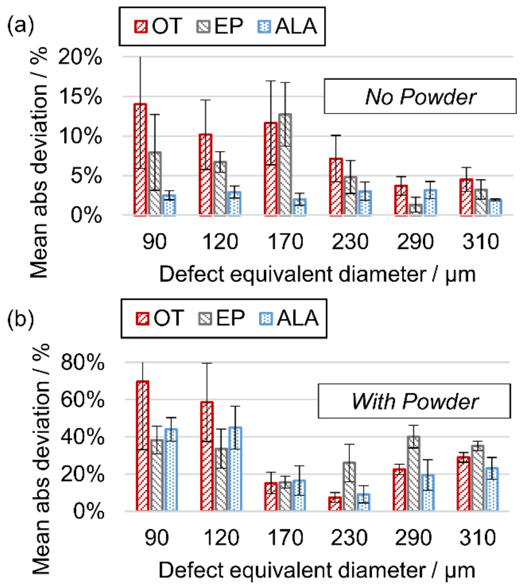

Figure 2. Mean absolute deviation obtained by the analyzed algorithms in the absence (a) and presence (b) of entrapped powder particles. Error bars represent ±1 standard deviation.

Moreover, ALA also led to a higher detection rate of smaller defects and can be leveraged to generate complete and accurate porosity labels, supporting the development of machine learning-based in-process PBF-LB/M monitoring solutions capable of predicting defect formation and associated size directly from process data acquired during fabrication.

Conversely, when defects contain entrapped powder (Fig. 2b), both OT and EP exhibited significant measurement deviations, exceeding 50% for the smallest pores in the case of OT. EP showed more stable results, with deviations ranging between 20% and 40%. The ALA approach yielded a slight overall improvement under these conditions. However, large deviations persisted for the smallest defects. These findings emphasize the detrimental impact of entrapped powder on segmentation accuracy, underscoring the limitations of traditional grey-value-based approaches and motivating the need to develop alternative methods, such as those leveraging machine learning.

4. Conclusions

This work investigated a novel reference object, specifically designed to reflect the complex morphology of PBF-LB/M porosities. A data fusion technique was implemented for the geometric calibration of artificial defects, enabling the use of the reference object both for evaluating the measurement accuracy of existing porosity analysis algorithms and for supporting the development of more accurate methodologies. In the absence of entrapped powder, the ALA approach achieved enhanced porosity measurement accuracy on smaller defects while maintaining robust performance across larger defect sizes.

The ALA method, potentially capable of providing comprehensive and accurate labelling of PBF-LB/M pores, is currently being applied to support the development of machine learning solutions for real-time prediction of pore formation and size, showing promising results when used with optical in-process monitoring data.

Future work will also focus on extending the use of the reference object to develop porosity analysis algorithms specifically tailored to improve the measurement accuracy of defects containing entrapped powder particles.

References

[1] Hao Kan, W., et al. (2022). A critical review on the effects of process-induced porosity on the mechanical properties of alloys fabricated by laser powder bed fusion. Journal of Materials Science 57: 9818-9865.

[2] Du Plessis, A., et al. (2018). X-Ray Microcomputed Tomography in Additive Manufacturing: A Review of the Current Technology and Applications. 3D Printing and Additive Manufacturing, 5(3): 227-247.

[3] Snyder, J. C., Thole, K. A. (2020). Understanding Laser Powder Bed Fusion Surface Roughness. Journal of Manufacturing Science and Engineering 142.

[4] Hermanek, P., et al. (2019). Traceable Porosity Measurements in Industrial Components Using X-Ray Computed Tomography. Journal of manufacturing Science and Engineering 141(5).

[5] Snow, Z., et al. (2020). Invited Review Article: Review of the formation and impact of flaws in powder bed fusion additive manufacturing. Additive Manufacturing 36.

[6] Bonato, N., et al. (2025). Enhanced tomographic porosity measurements in laser powder bed fusion metal parts using a novel reference object. Journal of Manufacturing Processes (submitted).

[7] Zanini, F., et al. (2024). New multi-function building plate for improving metal laser powder bed fusion by enhancing the alignment accuracy of in-process monitoring data, computed tomography measurements, and building volume geometry. The International Journal of Advanced Manufacturing Technology, 132(5), 2369-2380.

[8] ISO 15530-3:2011 Geometrical product specifications (GPS) - Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement - Use of calibrated workpieces or measurement standards. International Organization for Standardization, Geneve.