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Data-driven benchmarking methodology for evaluating PBF-LB/M machines with RMSD Analysis

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Abstract. Laser based powder bed fusion for metals (PBF-LB/M) is an industrial additive manufacturing (AM) method offering high-precision manufacturing for complex geometries. However, comparing the performance of different PBF-LB/M machines remains difficult, especially when machines are from different manufacturers. This study introduces a new benchmark artifact with standard features for facilitating the evaluation and comparison of machine performance. Two industrial PBF-LB/M machines, EOS M290 and Aconity3D MIDI+, were used to fabricate the part under similar conditions. The additively manufactured (AMed) samples were then inspected using 3D scanning metrology tools, and the results were analyzed using a method called root mean square deviation (RMSD) to measure how far each feature deviates from the original design. The results showed apparent differences in how each machine handled certain features and provide useful information for choosing the right machine based on part geometry.

1. Introduction

Many industries are adapting additive manufacturing (AM) technologies for their ability to produce complex, high-precision geometries without tooling restrictions [1]. Among them, laser based powder bed fusion for metals (PBF-LB/M) is a widely established process [2]. As more organizations adopt PBF-LB/M technology, selecting the right machine for a specific application becomes a growing challenge. This is especially problematic in multi-vendor workshop settings where machine architecture, scanning strategy, system, recoater, and process parameters interplay to influence part quality and consistency [3]. While machine suppliers provide technical datasheets and optimized parameters, this often lacks meaningful information about actual geometric performance [4]. Benchmark artifacts have been used extensively in literature to assess dimensional accuracy, feature resolution, and other metrics of performance of AM systems [5], [6], [7], [8], [9]. However, existing designs focus on process optimization, material properties validation, or academic evaluation of printability limits. These artifacts are too simple for any meaningful assessment between machines or too complex to be measured efficiently with commonly available tools [10]. Furthermore, many lack a clear evaluation framework to support decision-making [11]. This study introduces a compact benchmark artifact for cross-machine evaluation, fabricated on two industrial PBF-LB/M systems. Deviations were measured via high-resolution optical and laser scanning, and root mean square deviation (RMSD) was used as a consistent accuracy metric. The method provides industry with an accessible tool for machine assessment and offers academia a validated artifact and data-driven benchmarking framework.

2. Literature review

In the early 1990s, Kruth [7] introduced the first benchmark artifact for the geometric evaluation of additive manufacturing (AM) focusing on test parts for dimensional accuracy. Castillo [12] expanded by measuring wall thickness variation linked to impact of scan strategy and thermal distortion. These earliest studies dealt predominantly with single machine process validation. Moylan NIST [4] benchmark was designed to help compare different machines by checking accuracy and repeatability using a standard test part. However, its widespread adoption is limited due to its complexity, large size, and high measurement effort. NASA and academic partners [13] developed benchmarking artifacts with complex geometries for multi-machine comparison. Using a standard test part, Moshiri [5] compared five PBF-LB/M systems and noted considerable differences in fine hole and unsupported wall features. All benchmark artifacts in AM typically fall into three categories: geometrical, mechanical, or process-specific [14]. While useful for process or material validation, many designs combine features, making them time-consuming to measure, particularly in small labs or workshops. Most artifacts were created to tune system processes rather for machine comparison and lack consistent evaluation metrics or procedures to quantify geometric deviation. Rebaioli and Fassi [6] highlight the need for benchmark designs that balance measurement complexity with feasibility, enabling meaningful, comparable data. Prior studies rely on metrics like maximum deviation, mean absolute error (MAE), or pointwise tolerance for evaluating the benchmark artifact, which often fail to capture cumulative geometric error. This study uses RMSD for geometry-specific comparisons because of its statistical precision and greater sensitivity to larger deviations and captures local and global form errors simultaneously and returns scalar value suitable [15] for standard measure for benchmarking studies.

3. Material and method

This study expands on the prior benchmark designs from the literature by adding geometry types used for dimensional measurements evaluation, like holes, cylinders, and inclined surfaces. The artifact is compact to reduce build time and material usage [4], includes features measurable by surface-based optical scanning [16], and repeats features in multiple zones to assess spatial consistency [4]. The design excludes internal channels or computed tomography (CT) dependent geometries, ensuring compatibility with accessible laser and optical scanners. Each feature was dimensioned to match standard geometric dimensioning and tolerancing (GD&T) tolerances. These features were grouped and labeled to enable localized measurement, as shown in Figure 1.

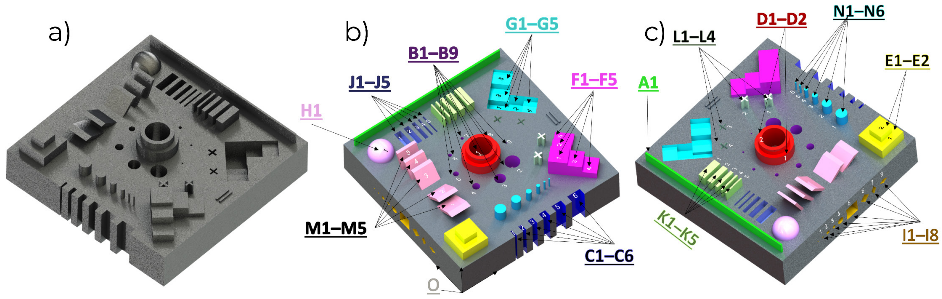

Figure 1. (a) CAD model of the benchmark artifact. (b,c) Color-coded feature groups are labeled.

While Table 1 summarizes the features in benchmark artifact in groups with number of instances, nominal dimensions, and tolerance focus groups for deviation and RMSD analysis.

Table 1. Summary of all the benchmark artifact features, grouped by category.

ID	Feature Type	Features	Dimensions / Angles	Target Tolerance
A	Long thin wall	A1	0.4 *mm* × 46 *mm* × 3 *mm*	Residual stress
B	Circular holes	B1–B9	Ø0.4 *mm* to Ø6 *mm*	Circularity / Diameters
C	Notches	C1–C6	0.5 *mm* to 4 *mm* widths	Fine feature accuracy
D	Cylindrical boss	D1–D2	Ø8 *mm*, Ø10 *mm*	Diameters
E	Square bosses	E1–E2	4×4×2 *mm*, 8×8×2 *mm*	Dimensional accuracy XY
F–G	Staircases (±)	F1–F5, G1–G5	1–5 *mm* step heights	Z-direction resolution
H	Hemispheres	H1	Ø7 *mm*	Blend accuracy
I	Lateral fine features	I1–I9	Ø0.4–2 *mm*, 1×1 *mm* squares	Fine feature printability
J	Slots	J1–J5	0.4 *mm* wide	Thin wall test
K	Thin walls	K1–K5	0.4 *mm* wide	Wall thickness
L	Crosses (out/in)	L1–L4	0.4 *mm* / 0.5 *mm* widths	Sharp edge accuracy
M	Inclinations	M1–M5	25° to 65° angles	Overhang & distortion
N	Pins & Circular bosses	N1–N6	Ø0.4 *mm* to Ø3 *mm*	Diameters
O	Outer base dimensions	O	50 × 50 × 10 *mm*	Global accuracy

Features were designed for GD&T-based evaluation and sized for compatibility with optical surface scanning.

The artifact measured 100 × 100 × 15 mm, sized to minimize material use while fitting standard PBF-LB/M volumes. Each feature was dimensioned according to standard GD&T tolerances and sized for compatibility with surface-based optical scanning tools. Complex internal geometries and support-dependent structures were intentionally excluded to ensure easy repeatability across different machines. The benchmark artefact was produced on two commercial PBF-LB/M machines—the EOS M 290 (EOS GmbH, Germany) and the Aconity3D MIDI+ (Aconity3D GmbH, Germany), see Figure 2.

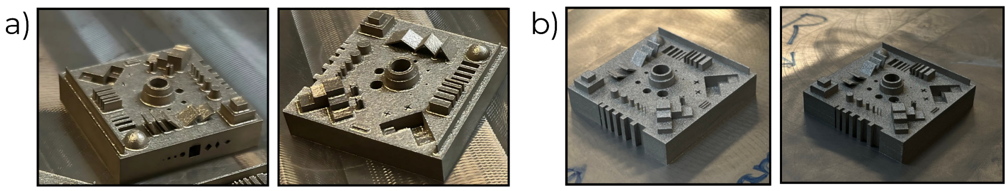

Figure 2. Benchmark artifact fabricated using (a) EOS M290 and (b) Aconity3D MIDI+ machines.

Two identical artifacts were fabricated on each platform from 316L stainless-steel powder (15–45 µm) using the same STL file and the machines' native slicers (EOSPRINT, Aconity Studio). Both builds used 40 µm layers, 0.11 mm hatch spacing, and ~1100 mm/s scan speed. Parts were oriented flat and required no post-processing. Figure 3 illustrates the alignment process used in this study, where high-density 3D point clouds captured using a ZEISS T-Scan 20 laser triangulation scanner were aligned to the original CAD model.

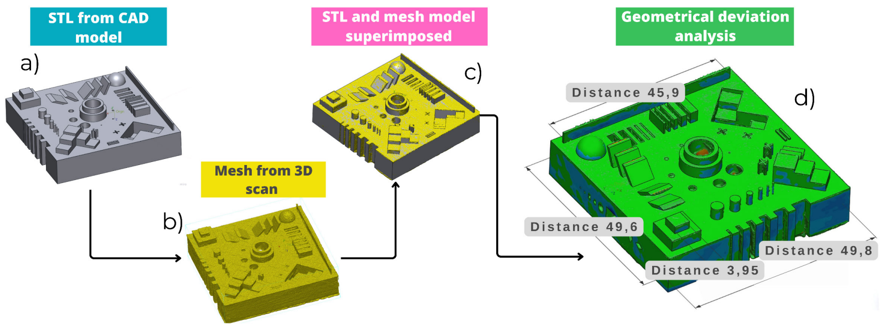

Figure 3. Workflow for deviation analysis using CAD and 3D scan models — (a) STL from CAD, (b) mesh from 3D scan, (c) superimposed models, (d) deviation map with measured distances.

A two-level metrology strategy was followed: one assessing dimensional accuracy and the other surface quality. The alignment was performed using initial registration and best-fit matching in Geomagic Control X, allowing precise measurement of how accurately each feature was built compared to the intended design. Surface roughness was measured using the Alicona InfiniteFocus G6 system. The Alicona software reconstructed 3D topographies by identifying sharp focus points across multiple vertical scans, as illustrated in Figure 4.

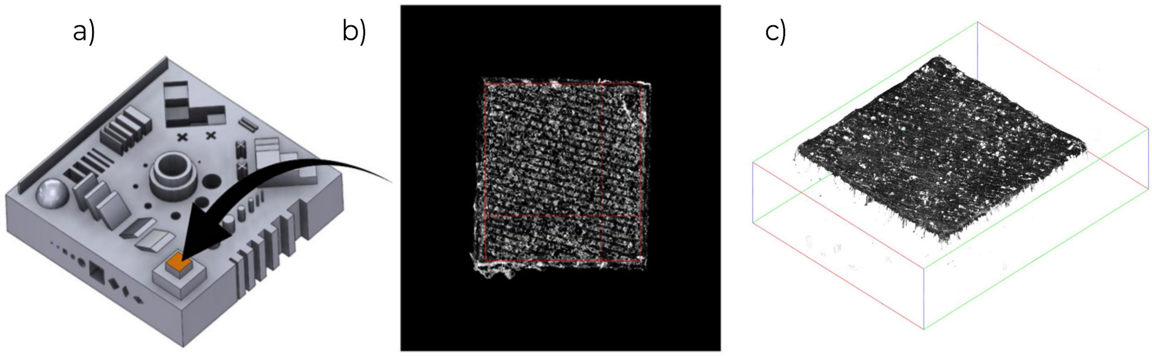

Figure 4. Surface roughness via Alicona G6: (a) roughness location on artifact; (b) scanned surface area; (c) 3D topographic profile.

A flat planar and overhanging surface were selected as optically accessible, support-free areas representative of AM quality and thermal behavior across both machines. Scanning was conducted at 20× magnification. The measurement process followed ISO 16610-71:2014, which applies a robust Gaussian regression filter to accurately capture and separate surface features of different scales. From these, areal roughness parameters such as *Sa* (arithmetic mean height) were calculated and used as the primary metric for comparing surface texture between machines.

After measuring deviations for each feature group along with surface roughness, and build time, RMSD values were measured separately and normalized to assess the dimensional accuracy between EOS M290 and Aconity3D MIDI+ (e.g., holes, walls, overhangs) using *equation (1).* Where x_i is the measured point, x_i^{ref} is the reference point on the CAD model, over n data points. RMSD aggregates both local deviations and global form error into a single scalar value, making it effective for comparing part accuracy across different machines and feature types. Surface-roughness RMSD was obtained by taking the root-mean-square of the differences between *Sa* readings gathered at identical surface locations on the EOS and MIDI+ artefacts. Build-time RMSD was calculated analogously, using the differences between slicer-predicted and actual job durations. In both cases, a smaller RMSD signals closer agreement and thus higher accuracy.

$$\mathrm{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - x_i^{\mathrm{ref}}\right)^2} \qquad (1)$$

4. Results and discussion

To show how the measurement strategy works, Figure 5 displays the deviations of the circular holes (B1–B9) listed earlier in Table 1.

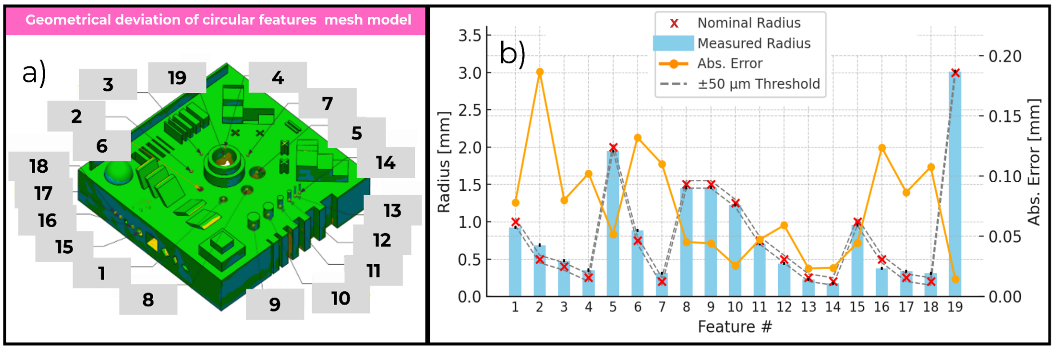

Figure 5. Circular feature deviation: (a) Circular feature labels; (b) Nominal vs. measured radii with error bars and ±0.05 *mm* threshold plotted around each nominal radius.

These circular hole features are typically sensitive to process parameters such as laser spot size, scan path accuracy, and contour definition. As shown in Figure 5b, nominal CAD radii (red crosses) are compared with measured values (blue bars), and absolute deviation is indicated in orange. A ±0.05 mm tolerance band is plotted as a grey zone around the nominal radius. While many features remain within tolerance, several display substantial deviation. Specifically, feature #10 (nominal = 1.25 mm, measured = 1.22 mm) shows a minimal deviation of 0.025 mm, indicating high geometric accuracy. In contrast, feature #2 (nominal = 0.50 mm, measured = 0.68 mm) deviates by 0.18 mm, which exceeds the tolerance by a wide margin. This highlights reduced precision when reproducing fine features, likely due to resolution limits or laser overexposure. These observations underline the value of localized feature analysis in benchmarking AM performance. RMSD values for each feature group were then calculated and are visualized in Figure 6 as a heatmap, where values closer to 0.00 indicate higher dimensional accuracy.

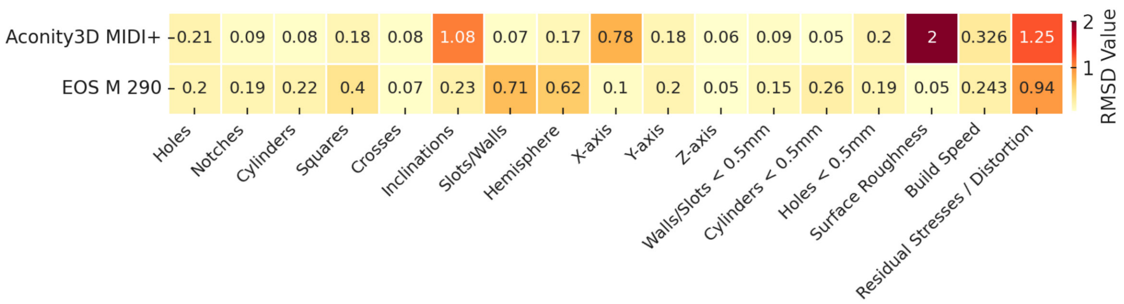

Figure 6. RMSD heatmap comparing EOS M290 and Aconity3D MIDI+.

EOS M290 yielded the lowest RMSD values for features most sensitive to thermal stability and scan-path transition: inclined surfaces (0.23 vs 1.08), residual-stress signs (0.94 vs 1.25), crosses (0.07 vs 0.08), Z-axis deviation (0.05 vs 0.06), and surface roughness (0.05 vs 2.00). These results reflect its production-grade sealed chamber, closed-loop thermal management, and optimized scan strategy. Aconity3D MIDI+ excelled where fine beam positioning was essential. It showed smaller RMSD values for hemispheres (0.17 vs 0.62), sub-0.5 mm cylinders (0.05 vs 0.26), thin walls/slots (0.07 vs 0.71), and features like notches (0.09 vs 0.19), nominal cylinders (0.08 vs 0.22), and squares (0.18 vs 0.40). This highlights its finer laser spot and flexible beam control, enabling precise energy delivery in narrow or curved areas. EOS, therefore, remains the safer choice for components needing minimal distortion and premium surface finish, while Aconity3D MIDI+ suits fine-featured parts like pins, thin walls, and internal channels. Aconity's open-frame and modular recoater likely caused local powder spreading and thermal inconsistencies, contributing to its scatter in surface roughness. Further testing with modified parameters could clarify these effects.

5. Conclusion

This research proposed a compact benchmark artifact and an RMSD-based assessment method for enabling geometric accuracy evaluation of PBF-LB/M machines. The EOS M290 performed outstandingly on distortion-sensitive features. Aconity3D MIDI+ demonstrated superior geometric accuracy on highly complex fine structural components. Each machine was evaluated and two artifacts from each machine yielded consistent replicate results, supporting comparison. The RMSD-based assessment method is practical and realistic, relying solely on accessible commercial scanners and software, making it especially useful for SMEs and multi-machine research. Notably, the entire benchmarking process from fabrication to testing occupies only one working day, favorable for useful industrial application. It enables feature level machine comparison based on actual print performance instead of just manufacturer-driven specifications and can be further enhanced by integrating multi criteria decision making (MCDA) to rank machines according to RMSD for each feature, tailoring system selection for production need.

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