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Benchmarking of geometric accuracy in PBF-LB/M: Approach to expand VDI 3405 for AlSi10Mg

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Abstract

The industrial adoption of Powder Bed Fusion with Laser Beam of Metals (PBF-LB/M), alongside specialized equipment tailored for different alloys and applications, necessitates a neutral, open benchmark to assess fabrication quality across different setups. This study aims to close the gap in the VDI 3405 Part 2.1 database for geometric dimensioning and tolerancing (GD&T) of AlSi10Mg. To this end, a modular test artifact is developed in collaboration between BAM and PTB. It addresses current geometric resolution limitations observed in a representative machine fleet, including machines from Nikon SLM, EOS, DMG Mori, and Aconity, as well as ensuring mandatory accessibility by various Non-Destructive Testing (NDT) methods. Designed according to DIN ISO/ASTM 52902, the artifact enables seamless communication of its geometry and facilitates the sharing of its Computer Aided Desing (CAD) model. To evaluate practical implications, an EOS M 300-4 and a DMG Mori Lasertec 30 are used to fabricate the artifact. The PBF-LB/M machines are calibrated per DIN ISO/ASTM 52930, using Original Equipment Manufacturer (OEM) qualified powder and corresponding parameter sets to replicate an industrial production environment. However, the evaluation of features used to describe the test artifact can be significantly affected by measurement procedure and its uncertainty. To mitigate variations, a test plan is established for X-ray Computed Tomography (XCT) and tactile surface roughness measurement, subsequently executed with devices from different OEMs. Preliminary results of the small Round Robin study provide insights into achievable geometric accuracy of AlSi10Mg, establishing a foundation for benchmarking PBF-LB/M machines and homogenizing performance across machines.

PBF-LB/M, Benchmark, IT grade, Geometric dimensioning and tolerancing, AlSi10Mg

1. Introduction

With the growing adoption of PBF-LB/M, machine-specific process parameters and alloy variations have significantly impacted achievable geometric accuracy [1]. Even for widely used alloys like AlSi10Mg, comprising about one-third of service provider feedstock, deviations of up to 32 % per quality criterion, like for $R_{p0.2}$ or R_z, are reported under identical build cycle layouts [2, 3]. These deviations stem from intrinsic performance differences between machines and parameter sets [3, 4]. While VDI 3405 Part 2.1 summarizes mechanical properties, it lacks standardized tolerance grades for GD&T. Comparative studies underscore the need for machine-agnostic benchmarks due to the high variability in achievable geometric accuracy [1]. Existing standards like VDI 3405 Part 3.2 focus on Design for Additive Manufacturing (DfAM) but do not provide comprehensive reference geometries, limiting PBF-LB/M machine comparability [5]. To address this gap, a modular benchmark artifact based on DIN ISO/ASTM 52902 is proposed [6]. Designed for compatibility with various machine types and multiple NDT methods, the artifact is fabricated on both an EOS M 300-4 and a DMG Mori Lasertec 30, each calibrated to DIN ISO/ASTM 52930 [7], mimicking an industrial environment. Evaluation is carried out in a small collaborative Round Robin study by BAM and PTB. Results, expressed in DIN 2796 tolerance grades and supplemented by surface roughness measurements, aim to support an extension of VDI 3405 Part 2.1 to include GD&T-based benchmarks [8].

2. Requirement management

To ensure compatibility with a broad range of PBF-LB/M machines from OEMs including Nikon SLM, EOS, DMG Mori, and Aconity, key machine specifications such as minimum build platform size, chamber dimensions, and geometric resolution, primarily governed by the laser beam diameter d_σ, are analyzed. Market data from additional OEMs is also incorporated to ensure broader applicability [9]. These specifications are used to derive the geometric constraints for a generically manufacturable test artifact, ensuring cross-platform applicability. Furthermore, fabrication expenses, including feedstock and operating time, are evaluated to support economic feasibility and reproducibility.

2.1. Measurement techniques

The AlSi10Mg feedstock is assessed by chemical composition and Particle Size Distribution (PSD), in accordance with current state-of-the-art [10, 11]. Following condition and powder bed image monitored fabrication of the artifact, GD&T features are evaluated using industrial XCT systems, specifically the Nikon MCT 225 and diondo dxMAX, each calibrated to a voxel size of approximately ≈ 35 µm³. XCT data is processed using VGStudio MAX 2024.3. Surface roughness is analyzed using tactile profilometers MarSurf GD 120 and Hommel T8000. All measurements are conducted within a Round Robin scheme to reduce operator and system bias, thereby supporting reproducibility and standardization.

2.2. Benchmark test artifact

Test artifacts are essential in Additive Manufacturing (AM) research and qualification, enabling standardized verification of process capabilities [12, 13]. GD&T is particularly critical to foster industry confidence in AM-produced components. Artifacts typically incorporate features to assess system performance limits, such as maximum overhang angle, minimum feature size, repeatability, flatness, and cylindricity [6, 12, 13]. Due to the absence of a universal test artifact suitable for all AM processes, customized benchmarks are often developed to reflect specific machine characteristics. While many studies [14-16] focus on geometric accuracy across processes, gaps remain in data collection specific to PBF-LB/M, contributing to the lack of a widely accepted benchmark. In 2012, the National Institute of Standards and Technology (NIST) introduced a test artifact with a flat base and geometric features to assess GD&T and resolution [12, 13]. This is followed by the ISO/ASTM 52902 standard, which formalized test geometries for geometric capability assessment [6]. A widely used test specimen based on this standard is dimensioned 140.0 mm × 140.0 mm × 31.8 mm, designed for broad PBF-LB/M compatibility [14]. However, the size of this standard artifact limits its evaluation by high-resolution XCT, especially for dense materials. To overcome this, a compact artifact based on ISO/ASTM 52902 is developed in this work, see Figure 1. The design is dimensioned 55 mm × 60 mm × 16 mm, including a 5 mm high base extension and incorporates key geometric features such as raised and recessed cylinders, wall thickness variations, slots, linear distances, concentric rings, and angled surface roughness fields [6]. All features are uniquely identified and designed for accessibility, ensuring compatibility with various NDT methods. Undercuts and aspect ratios > 4:1 are avoided, except for slots, which can be measured tactilely using gauges when XCT is not available. Alignment markings enable consistent orientation within the Machine Coordinate System (MCS) and adjustment relative to shielding gas flow.

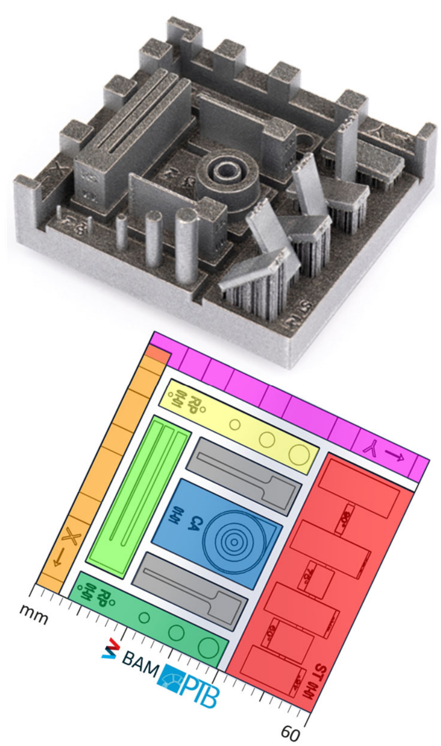

Figure 1. Test artifact fabricated out of AlSi10Mg and the geometric features of Table 1 assigned in the top view

Table 1. Geometric features of the test artifact

Feature	Description
Length test specimens LA_X_#	Rectangular step gauge blocks with by 2.5 mm incrementally increasing distances between the blocks. The unidirectional distances are (A1-A3: 10 mm, A1-A5: 22.5 mm, A1-A7: 37.5 mm) and the bidirectional ones are (A1-A2: 5 mm, A1-A4: 17.5 mm, A1-A6: 32.5 mm and A1-A8: 50 mm) in the X and Y directions
Length test specimens LA_Y_#	
Pins RPp_#	Five cylindrical pins with diameters of 0.8 mm, 1 mm, 2 mm, 3 mm and 4 mm
Holes RPn_#	Five cylindrical holes with diameters of 0.8 mm, 1 mm, 2 mm, 3 mm and 4 mm
Slot widths RS_#	Two slot widths with spacings of 0.4 mm and 0.8 mm
Wall thickness RR_#	Two walls with wall thicknesses of 0.8 mm and 1.2 mm
Hollow cylinder CA_#_#	These features include a hollow cylinder with outer and inner diameters (11.75 mm and 7.5 mm respectively) and an inner hollow cylinder with outer and inner diameters (5.1 mm and 3.5 mm)
Surface structures SA_#	Seven surfaces at different angles 0°, 15°, 30°, 45°, 60°, 75° and 90° to investigate the influence of inclined surfaces on surface roughness

3. Fabrication across platforms

A comparative analysis of PBF-LB/M machines, process parameters, and powder specifications is conducted for the EOS M 300-4 and the DMG Mori Lasertec 30. Despite variations in laser unit configuration, layer thickness l_z and PSD, both PBF-LB/M machines process AlSi10Mg using OEM-validated parameter sets. Volumetric Energy Density (VED) and theoretical Build-Up Rate (BUR) are used to characterize the energy input. The setup of the fabrication including PSD and preheating conditions, are summarized in Table 2.

$$VED = \frac{P_L}{h_s \times v_s \times t_z} \quad (1)$$

$$BUR = h_s \times v_s \times t_z \quad (2)$$

Table 2. Comparison of the fabrication setup

Institute	**BAM**	**PTB**
AlSi10Mg chemistry	According to DIN EN 1706	According to DIN EN 1706
AlSi10Mg PSD	d_{10} = 25 µm d_{50} = 44 µm d_{90} = 73 µm	d_{10} = 19 µm d_{50} = 40 µm d_{90} = 62 µm
PBF-LB/M machine	**EOS M 300-4**	**DMG Mori Lasertec 30**
Shielding gas	Argon	**Argon**
Global scaling X	0.35 %	0.55 %
Global scaling Y	0.37 %	0.35 %
Beam diameter d_σ	≈ 84 µm	≈ 80 µm
Beam offset	0.2 mm	0.19 mm
Layer thickness l_z	60 µm	40 µm
Parameter set designation	**AlSi10Mg_060_CoreM304_102**	**3.2381_40µm_Nr.9**
Pre-heating	165 °C	150 °C
VED	34 J/mm³	33 J/mm³
BUR per laser	39 cm³/h	33 cm³/h

The artifacts are centrally positioned within the respective MCS on the build platforms, composed of AlSiMg4.5Mn0.7 for the EOS M300-4 and AlSi10Mg for the DMG Mori Lasertec 30. To ensure consistency across different PBF-LB/M machines, each artifact is assigned to a single laser unit. To evaluate scalability and robustness, particularly regarding non-standard measurement line lengths in surface roughness measurements, also a by factor 1.8 enlarged subsection of the surface structure SA_# is included, fulfilling the formal requirements of ISO 4287 [17]. No abnormalities occur during fabrication. Both PBF/LB-M machines remain within intrinsic process thresholds, including build chamber temperature, recoater torque, and shielding gas flow. Powder bed monitoring systems report no errors related to recoating or exposure. The fabrication time per artifact is approximately 1 h, with a molten powder mass of 100 g, subject to minor machine-specific variations.

4. Evaluation via Round Robin

4.1. Test plans

A within the Round Robin developed test plan ensures consistent evaluation of the artifact. It is divided into defined sections, each mapped to specific GD&T and surface roughness criteria, see Table 1, enabling targeted assessment of features such as hole and pin diameters, wall thicknesses, step gauges, and inclined surfaces. XCT data reconstruction uses optimized thresholding based on grey-value gradients and Gaussian surface criteria to minimize imaging artifacts. Dimensional analysis is conducted performing a best-fit of the reconstructed volume to the CAD model and evaluated across multiple software platforms in accordance with ISO 1101 [18] Surface roughness is measured via contact profilometry (S-L profile) using a λc cut off of 8 mm and λs of 8 µm, with a minimum of five profiles recorded per inclined top plane of the surface structure to ensure statistical robustness. The Round Robin study is based on this test plan, enabling consistent comparison across machines and participants. It supports IT grade classification and surface quality assessment, with porosity values required to fall within the distribution defined by VDI 3405 Part 3.2 [3] as a requirement for further evaluation.

4.2. GD&T

The achieved IT grades for the evaluated features correspond to IT10 for one PBF-LB/M machine and IT11 for the other, based on ISO 286-1 and the assumption of a fundamental deviation of zero as target criterium, in accordance with DIN 2796, as presented in Table 3 [8, 19].

Table 3. Excerpt of DIN 2796 for nominal dimensions of the test artifact

Tolerance class	Limits for nominal dimensions in mm			
	from 0.5 until 3	from 3 until 6	from 6 until 30	from 30 until 120
fine	± 0.05	± 0.05	± 0.10	± 0.15
medium	± 0.10	± 0.10	± 0.20	± 0.30
coarse	± 0.20	± 0.30	± 0.50	± 0.80
very coarse	-	± 0.50	± 1.00	± 1.50

The significance of these findings is supported by a mean deviation $\overline{x}$ of 14 µm and a standard deviation s of 11 µm per artifact across all measured features, corresponding approximately to four times the edge length of one voxel, encompassing both XCT reconstruction and evaluation steps. This indicates that variations introduced by the measurement processes are negligible relative to the overall geometric deviations, which are presented in Figure 2.

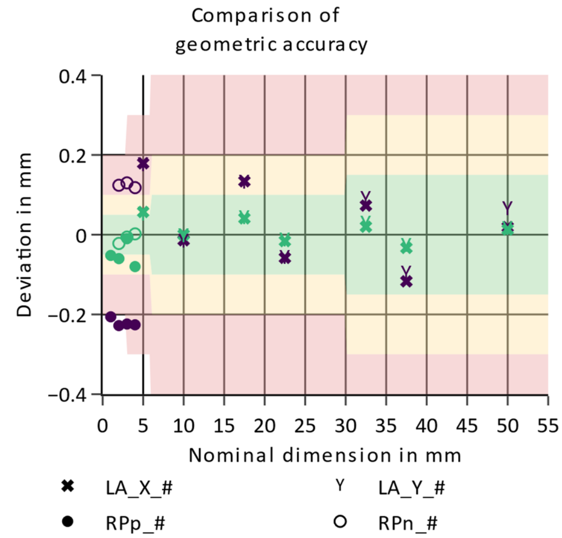

Figure 2. Achieved geometric accuracy for the geometric features of the artifact described in Table 1 with fabrication set up of Table 2, tolerance grades are indicated by colour, green for fine, yellow for medium, and red for coarse, in accordance with DIN 2769

4.3. Surface roughness

Surface roughness is assessed on inclined surfaces from 0° to 90° for both the original and the scaled SA_# artifact geometries. The results confirm that the artifact enables reproducible surface quality evaluation across different PBF-LB/M machines and configurations. This is supported by a mean deviation $\overline{x}$ of 2.8 µm and a standard deviation s of 1.8 µm between the two measurement processes, accounting for both profile filtering and slight positional differences in measurement allocation. As illustrated in Figure 3, a consistent trend is observed for the PTB artifacts. The surface roughness characterized by Ra decreases with increasing build-up angle. At 0°, roughness values reach approximately 30 µm, while at 90°, values drop to around 6 µm. Comparison between the normal and scaled artifact sections reveals no significant differences; across all angles, deviations remain within ± 10 µm. With the limitation that the informative value of the artifact depends on the applied layer thickness l_z and the PSD, it still proves suitable for PBF/LB-M machines using fine layers and narrow PSDs. Under these conditions, the original and by factor 1.8 enlarged surface structures SA_# yield comparable results, as demonstrated in Figure 3.

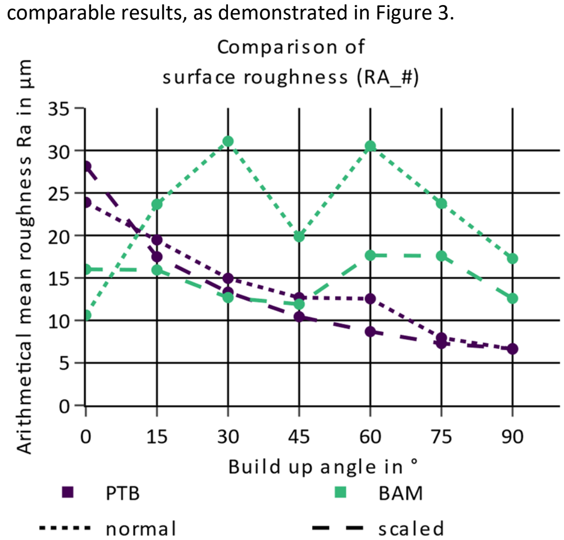

Figure 3. Achieved surface roughness for the scaled and the original geometric features of the artifact described in Table 1 with fabrication set up of Table 2

In contrast, the other PBF-LB/M machine, which employs a coarser PSD and higher layer thicknesses l_z exhibits noticeable deviations of up to 20 µm between the two artifact versions and generally higher surface roughness.

5. Strategy to homogenize the machine performance

To reduce machine-specific deviations in GD&T, global scaling and beam offset adjustments were applied to the PBF-LB/M machine achieving IT 11. Based on observed deviations and prior findings, scaling was set to + 0.5 % in the X-direction and + 0.35 % in the Y-direction, with a beam offset adjustment of + 0.05 mm [15]. Following the application of scaling and beam offset corrections, both PBF-LB/M machines achieved a matching IT grade of 10. These adjustments resulted in a reduction of geometric deviations, demonstrating that machine-specific compensation enables alignment with finer tolerance classes, as visualized in Figure 4

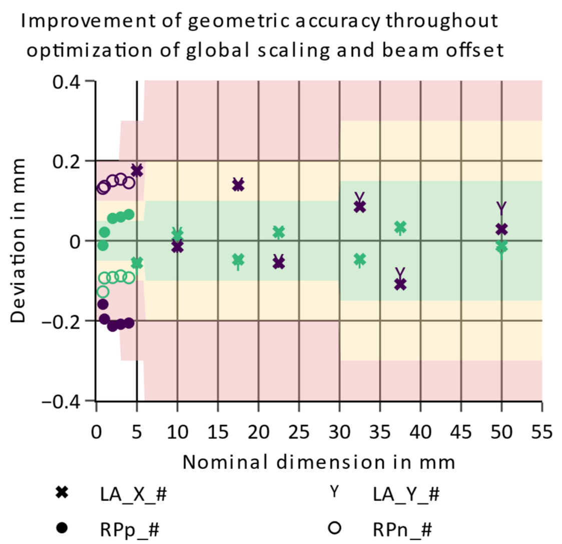

Figure 4. Achieved geometric accuracy after optimization of the global scaling and the beam offset on the DMG Mori Lasertec 30, tolerance grades are indicated by colour, green for fine, yellow for medium, and red for coarse, in accordance with DIN 2769

6. Conclusion

In In terms of GD&T, beam offset along the scaling is identified as the dominant parameter for alignment of machine performance. In contrast, deviations in surface roughness are primarily attributed to variations in PSD and layer thickness l_z, as detailed in Table 2. The presence of coarser particles, though still sufficiently small to undergo sintering, introduces geometric inaccuracies that cannot be mitigated without changes in the fabrication setup [16]. The artifact itself is characterized by low material consumption and high accessibility, achieved using standardized geometric primitives as defined in DIN ISO/ASTM 52902 [6]. Its adoption facilitates benchmarking of PBF-LB/M machines and supports ongoing efforts to harmonize performance across platforms, particularly with respect to GD&T criteria, as demonstrated. Once the test specimen is standardized, there is a clear need for holistic test plans that incorporate application-specific compensation strategies. These are required to reliably extract geometric elements, which are then subject to GD&T evaluation, from the spatial data provided by the measurement systems. This is essential not only to account for measurement uncertainty, as observed in the small Round Robin study, but also to enable standardized, reliable, and comparable GD&T evaluations.

References

[1] Krasniqi, M., Löffler, F.: Comprehensive study on statistical methods for optimization of process parameters and material properties of AlSi10Mg in laser powder bed fusion. Discover Mechanical Engineering 3, 42 (2024)

[2] Wohlers, T.T., Associates, W., Campbell, I., Diegel, O., Huff, R., Kowen, J., Mostow, N., Staff, W.A.: Wohlers Report 2024: 3D Printing and Additive Manufacturing Global State of the Industry. Wohlers Associates (2024)

[3] VDI 3405 Blatt 2.1 August 2020 Additive Fertigungsverfahren Pulverbettbasiertes Schmelzen von Metall mittels Laserstrahl (PBF-LB M) Materialkenndatenblatt Aluminiumlegierung AlSi10Mg (2020)

[4] Schneider, M., Bettge, D., Binder, M., Dollmeier, K., Dreyer, M., Hilgenberg, K., Klöden, B., Schlingmann, T., Schmidt, J.: Reproducibility and Scattering in Additive Manufacturing: Results from a Round Robin on PBF-LB/M AlSi10Mg Alloy. Practical Metallography 59, 580–614 (2022)

[5] VDI 3405 Blatt 3.2 Entwurf Juli 2019 Additive Fertigungsverfahren Gestaltungsempfehlungen Prüfkörper und Prüfmerkmale für limitierende Geometrielemente (2019)

[6] DIN EN ISO ASTM 52902 Entwurf Januar 2022 Additive Fertigung Testkörper Geometrische Leistungsbewertung additiver Fertigungssysteme (2022)

[7] DIN CEN ISO ASTM TS 52930 April 2022 Additive Fertigung Grundlagen der Qualifizierung Installation Funktion und Leistung (IQ OQ PQ) von PBF-LB Anlagen (2022)

[8] DIN 2769 April 2023 Geometrische Produktspezifikation (GPS) Allgemeintoleranzen Tabellenwerte für geometrische Toleranzen und Toleranzen für Längen und Winkelgrößenmaße ohne individuelle Toleranzangabe (2023)

[9] Khorasani, A., Gibson, I., Veetil, J.K., Ghasemi, A.H.: A review of technological improvements in laser-based powder bed fusion of metal printers. The International Journal of Advanced Manufacturing Technology 108, 191–209 (2020)

[10] DIN EN 1706 Oktober 2021 Aluminium und Aluminiumlegierungen Gussstücke chemische Zusammensetzung und mechanische Eigenschaften (2021)

[11] DIN ISO 13320 Dezember 2022 Partikelgrößenanalyse Laserbeugungsverfahren. vol. DIN ISO 13320 (2022)

[12] Moylan, S., Slotwinski, J., Cooke, A., Jurrens, K., Donmez, M.A.: An additive manufacturing test artifact. Journal of research of the National Institute of Standards and Technology 119, 429 (2014)

[13] Taylor, H., Garibay, E., Wicker, R.: Toward a common laser powder bed fusion qualification test artifact. Additive Manufacturing 39, 101803 (2021)

[14] Gradl, P.R., Tinker, D.C., Ivester, J., Skinner, S.W., Teasley, T., Bili, J.L.: Geometric feature reproducibility for laser powder bed fusion (L-PBF) additive manufacturing with Inconel 718. Additive Manufacturing 47, 102305 (2021)

[15] Krasniqi, M., Löffler, F., Tutsch, R.: Influence of scanning strategies on dimensional accuracy in laser powder bed fusion. Measurement: Sensors 101840 (2025)

[16] Riener, K., Albrecht, N., Ziegelmeier, S., Ramakrishnan, R., Haferkamp, L., Spierings, A.B., Leichtfried, G.J.: Influence of particle size distribution and morphology on the properties of the powder feedstock as well as of AlSi10Mg parts produced by laser powder bed fusion (LPBF). Additive Manufacturing 34, 101286 (2020)

[17] DIN EN ISO 4287 Juli 2010 Geometrische Produktspezifikation Oberflächenbeschaffenheit Tastschnittverfahren Bennenung Definitionen und Kenngrößen der Oberflächenbeschaffenheit (2010)

[18] DIN EN ISO 1101 September 2017 Geometrische Produktspezifikation (GPS) Geometrische Tolerierung von Form Richtung Ort und Lauf (2017)

[19] DIN EN ISO 286-1 September 2019 Geometrische Produktspezifikation GPS ISO Toleranzsysteme für Längenmaße Teil 1 Grundlagen für Toleranzen Abmaße und Passungen (2019)