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Impact of association criteria specifications on inspection of hole features in laser powder bed fusion

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Abstract
This study investigates the influence of build orientation and measurement methodology on the dimensional conformance of hole features fabricated using metal powder bed fusion with laser beam (PBF-LB). Identical parts containing a nominal hole diameter of 7.874 mm were built in five different orientations, each with three replicates. Hole diameters were assessed using calipers in two directions and then measured using a coordinate measuring machine (CMM). For the CMM point cloud data, least-square, maximum inscribed, and minimum circumscribed size association criteria were used to compute the hole diameters. The calculated values from each measurement scenario were compared against the designed diameter and a symmetric tolerance of ± 0.1 mm. Results indicate that the choice of association criteria alone can change the measured diameter for the same hole profile by almost 1 mm. This brief study provides practical insight that can be leveraged to better convey design intent and inform inspection protocols for functionally critical hole features in PBF-LB parts.

Dimensional inspection, hole measurements, association criteria, tolerancing, laser powder bed fusion

1. Introduction

Simple hole features that are easily produced and verified in traditional machining processes can become challenging to fabricate and inspect when created with metal powder bed fusion with laser beam (PBF-LB). Compared to subtractive processes like drilling, boring, and reaming, PBF-LB holes exhibit significantly higher surface roughness and form errors, including stair-stepping, dross formation, and anisotropic thermal distortion [1-3], due to process characteristics. This makes the interpretation of the size or diameter of a PBF-LB hole largely dependent on how an ideal feature geometry (circle or cylinder) is associated with the measurement data.

ISO 14405-1:2016 provides more than 15 different association criteria (linear size specification modifiers) that can be used to convey functional intent and inspection protocols on technical drawings [4,5]. The default association criterion for a diameter tolerance without a modifier (e.g., “Ø10 mm ± 0.1 mm”) typically implies that the inspection can and should be carried out using a two-point measurement (e.g., manual gauging with calipers) which can also be conveyed explicitly by adding the two-point size (LP) modifier beside the size tolerance (e.g., “Ø10 mm ± 1 mm (LP)”). But in some cases, inspection can only be performed using coordinate measurement system data (e.g., from a coordinate measurement machine (CMM), structured light scanners, or x-ray computed tomography (XCT)), and different association criteria modifiers are required to convey design intent. For example, the maximum inscribed size association modifier (GX) provides the largest-diameter circle that can fit entirely within the measured hole profile. This can be used to simulate an assembly condition and ensure that a sphere or cylinder of known diameter will fit. Controlling the diameter with the GX modifier is appropriate when physical clearance is required for the as-built part to function properly, such as in self-contained assemblies or fluid channels.

In contrast, a least-square association criterion (GG), which is the default criterion in most inspection software, may not always capture this functional requirement since the objective function results in a best-fit circle that may not be physically accurate. Alternatively, the minimum circumscribed size, denoted by the modifier (GN), represents the smallest-diameter circle that fully encloses the locus of the sampled points. The GN diameter could be used to control and optimize clearances between parallel internal channels or to streamline post-processing operations. However, for PBF-LB part features, substituting one association criterion for another can have a statistically significant impact on a diameter measurement result and, consequently, on part conformance and/or functional performance. This brief study expands on previous research established by [6] and evaluates a specific PBF-LB part feature using both manual gauging and a CMM to investigate the effect of association criteria specifications on part inspection outcomes. The fabrication and measurement details are first summarized, and then followed by the measurement results, conclusions, and detailed future work directions.

2. Methodology

Exemplified in Figure 1, parts with a nominally designed hole diameter of 7.874 mm were fabricated in five build orientations: Vertical Hole Up (VHU), Vertical Hole Down (VHD), Vertical Tilted 45° (VT45), Horizontal Tilted 45° (HT45), and Horizontal (H). Support structures used for the different part orientations are colored blue in Figure 1(a). Each orientation was produced (a total of 15 parts, with 3 repeats for each orientation) using an XM200G printer by Xact Metal and 316L stainless steel powder,

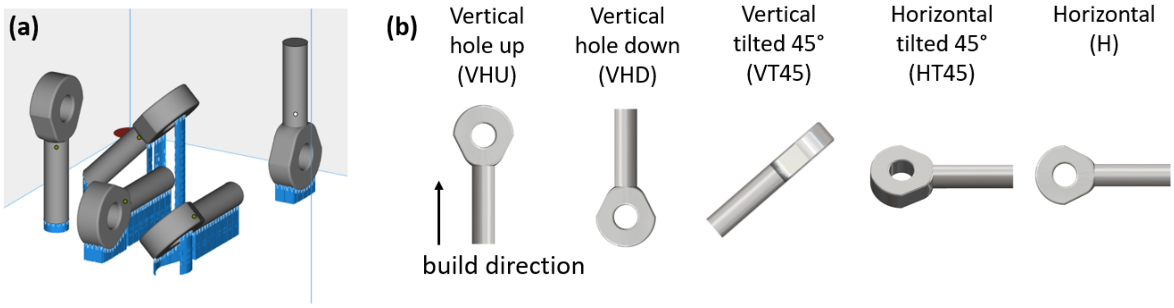

Figure 1. (a) Example of part layout and support structures. (b) Naming conventions for the different build orientations: vertical hole up (VHU), vertical hole down (VHD), vertical tilted 45° (VT45), horizontal tilted 45° (HT45), and horizontal (H).

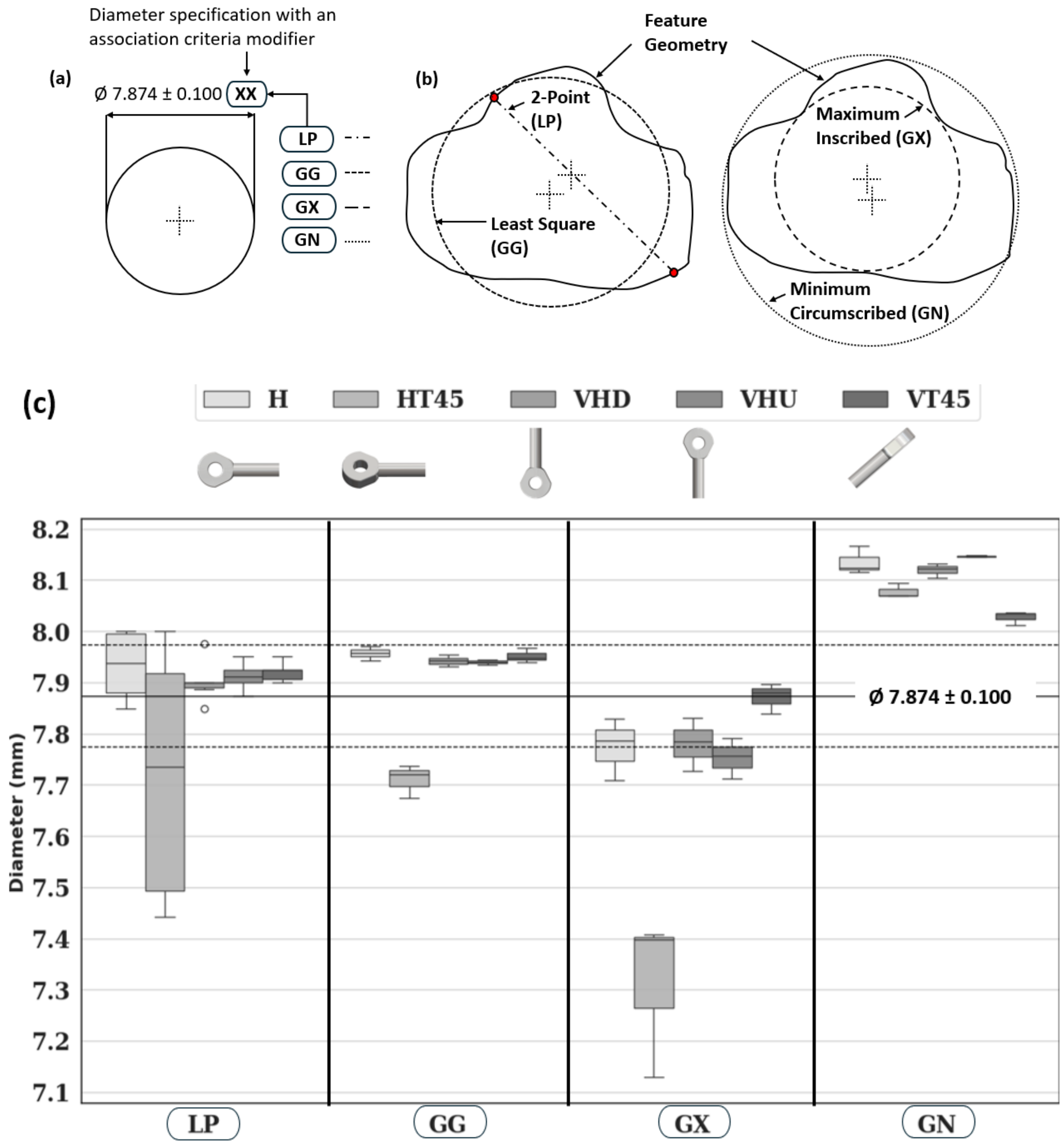

Figure 2. (a) Example of how an association criteria modifier can be placed beside size tolerance to control the diameter measurement result. (b) Example of circle fit based on different association criteria for the same non-ideal hole profile. (c) Measurement results for two-point (LP) caliper inspection and inspection based on CMM data for the different association criteria: least-squares (GG), maximum inscribed (GX), and minimum circumscribed (GN) for the 15 parts and five build orientations.

with the PBF-LB vendor-recommended process parameters given in Table 1. After separating the parts from the build plate using wire electrical discharge machining (EDM) and manually removing the support structures, each sample was subjected to a routine shot blasting operation. This involved blasting with a handheld gun (~80 psi, 7.9 mm nozzle) for 1 min to 3 min using a 2:1 mixture of glass beads (80 µm to 140 µm) and aluminum oxide (~63 µm) to remove loose particles prior to measuring the hole features.

Table 1 Process parameters used for part fabrication

Parameters	Value (unit)
Material	316L stainless steel
Laser Power	180 (W)
Laser Beam Diameter	50 (µm)
Scan Speed	2350 (mm/s)
Hatch Spacing	40 (µm)
Programmed Layer Thickness	30 (µm)
Stripe Width	20 (mm)
Layer Rotations	67 (°)
Build Plate Temperature	100 (°C)
Powder Size Distribution	(D_{10}-19, D_{50}-31, D_{90}-50) (µm)

Inner diameter measurements were initially performed using a dial caliper using the upper knife edge jaws across two orthogonal directions, parallel and perpendicular to the part's vertical axis, representing a two-point inspection at two different measurement orientations. The measurements are assumed to have a standard uncertainty of 7.3 µm (k=1), which is derived from half the smallest graduation, assuming a rectangular distribution. Subsequent CMM measurements were conducted using a Leitz Infinity 12107 equipped with an HP-S-X5-HD probe. This system has a manufacturer stated $E_{0,\ MPE}$ of (0.3 + L/1000) µm, where L is the measured length in mm, a $P_{Form.Sph.1\times25:SS:Tact}$ of 0.4 µm, and a $P_{Size.Sph.1\times25:SS:Tact}$ of 0.3 µm, as specified in ISO 10360-2:2009 and ISO 10360-5:2020 [7,8]. A 1.5 mm diameter ruby stylus was used for the measurement. However, the previously listed P values are only valid using specific manufacturer stated styli (very round ⌀3 and ⌀5 mm styli). Probing performance was verified by a 49-point measurement on reference sphere (⌀30mm, roundness < 80nm) and a 100-point measurement of the equator of the sphere in the XY plane (similar to the component measurements). Both tests were repeated multiple times and produced form values <0.5 µm. For each hole, profiles were acquired at 2 mm, 4 mm, and 6 mm depths with 100 evenly spaced points per profile. The diameter of each hole was calculated using the least-square (GG), maximum inscribed (GX), and minimum circumscribed (GN) size association criteria within the CMM software (QUINDOS). Temperature monitoring during the measurement was completed using 4 sensors each with a standard uncertainty of 0.015 °C. The average of these sensors over the course of the measurement was 20.002 °C and the range of these measured values was ± 0.030 °C. Therefore, correction to nominal size and the uncertainty due to thermal effects are negligible considering the small diameter.

3. Results

The dial caliper measurements (LP) in Figure 2 suggest that the HT45-oriented parts exhibited the lowest geometric accuracy on average and had the highest variability across replicates. For the horizontal orientation (H), each sample exceeded the ± 0.1 mm tolerance when measured along the vertical axis of the part but fell within the specification limits when measured at a perpendicular orientation. In contrast, VHU, VHD, and VT45 generally yielded consistent results that were mostly within the ± 0.1 mm tolerance band, regardless of measurement orientation. The mean and standard deviation of the measured diameter across all build orientations and measurement method were (LP) 7.877 mm ± 0.135 mm, (GG) 7.900 mm ± 0.096 mm, (GX) 7.698 mm ± 0.208 mm, and (GN) 8.101 mm ± 0.045 mm. All of the least-squares diameters (GG) were within the ± 0.1 mm tolerance, except for the HT45-oriented parts. On average, the maximum inscribed (GX) diameters were ~2.5 % smaller, and the minimum circumscribed (GN) diameters were ~2.5 % larger than the least-square (GG) diameters — although in one case, the diameter for the same hole profile data decreased by ~7 % for the GX criteria and increased by ~5 % for the GN criteria.

3.1. Hole Profiles and Form Error

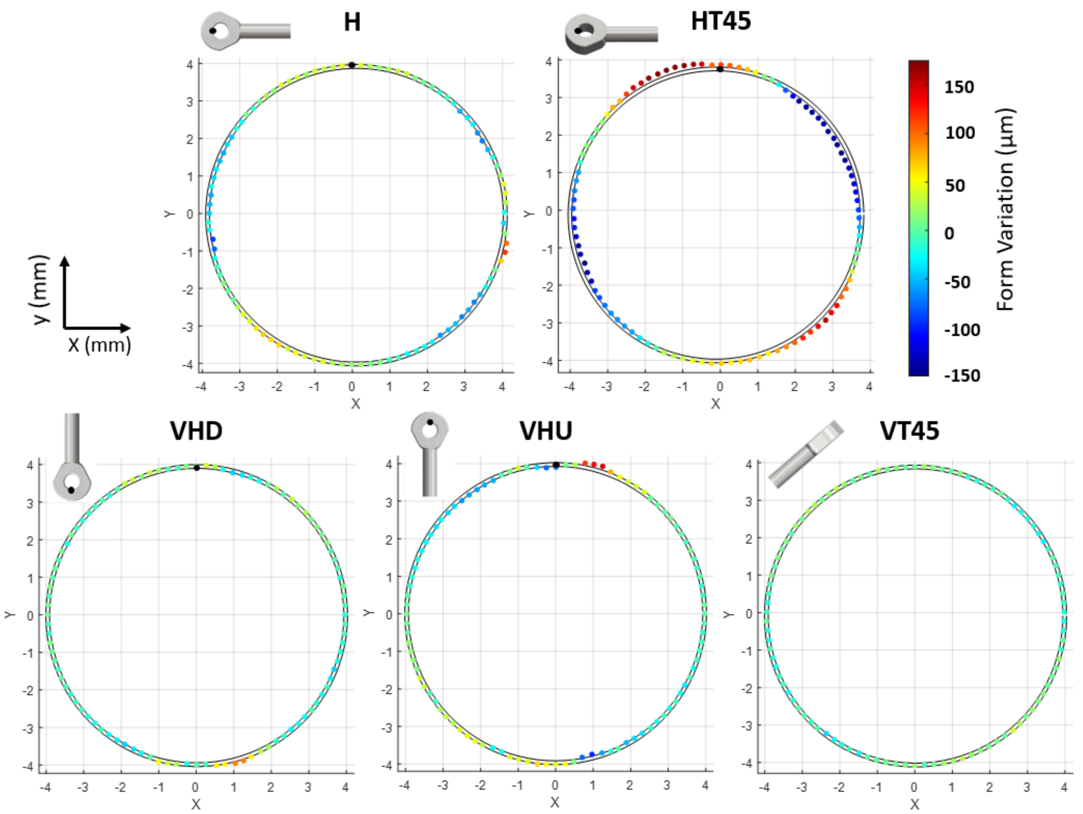

Figure 3. Example of measured hole profiles compared to the designed diameter and ± 0.1 mm tolerance band denoted by the two black circles.

Figure 3 compares the designed diameter to the measured hole profiles at each build orientation, sampled at different locations within the hole (6 mm from the top face). Deviations from the ideal profile are most pronounced for the HT45 orientation. While VT45 appears to have the fewest, this was not expected due to less overhanging surface. The amount of form error across all parts, according to the (GG) association criteria, ranged between a minimum of 0.078 mm for the VT45 orientation and up to 0.598 mm for the HT45 orientation, with an average and standard deviation of 0.263 mm ± 0.129 mm across all parts. Larger form errors are expected for as-built holes that have not been subjected to any type of post shot-blasting and cleaning operations.

4. Conclusions

Designers can and should utilize association criteria modifiers to convey design intent and control the size of additively manufactured hole features, ensuring proper function in various applications including clearances for powder evacuation, post-machining, and internal channels and assemblies. However, the findings of this work indicate that substituting one association criterion or inspection method for another can significantly impact measurement results, resulting in a diameter measurement that is either within or outside specified tolerance limits, even on the same point cloud data. This has implications for process optimization efforts that rely on measurement results to inform profile or diameter compensations to ensure proper as-built sizes. Specifically, using different associations such as least-squares (GG), maximum inscribed (GX), or minimum circumscribed (GN) size associations — which differ in their definition of the hole diameter — can necessitate different amounts of compensation within the manufacturing process to satisfy a diameter specification. Furthermore, the ability to transfer model-based definitions directly from a computer-aided design (CAD) model to the additive manufacturing (AM) slicing or build preparation software to apply diameter compensations automatically based on the specified association criteria would be a desirable feature. The study results highlighted the importance of careful design, tolerancing, and inspection considerations for critical hole features in PBF-LB components.

5. Future Work

To generalize these findings, future work includes the design of a comprehensive multi-channel artifact with different diameters and orientations. The artifact will be optimized to streamline inspections via hard gauging. Channels will be inspected with increments of different precision metal spheres that can be used to check clearances throughout. Off-the-shelf spheres, gauge pins, and plug gauges could be included as part of a kit. The artifact should enable AM users to rapidly characterize and benchmark the performance of their specific PBF-LB system and material setup. This could enable dimensional inspection, qualification, and optimization of internal channels without the explicit need to use XCT, which is prohibitively expensive and inaccessible for most manufacturers.

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