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Dimensional measurements of additive manufacturing parts: A comparison of X-ray computed tomography and coordinate-measuring system using physical and simulation approaches

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Abstract
The purpose of this study is to assess the effectiveness of X-ray Computed Tomography (XCT) in measuring dimensions of additively manufactured (AM) parts, and compare it to a well-established tactile coordinate-measuring system (CMS). The study investigates three factors: XCT beam hardening, XCT voxel size scale error, and CMS mechanical filtering effect. The performance of XCT and CMS in measuring a half-smooth and half-rough AM hollow cylinder is compared. To complement physical measurements, simulation methods are used to investigate the individual impacts of XCT beam hardening and CMS mechanical filtering effect. The physical experimental results show that the elimination of XCT beam hardening aids in obtaining accurate internal dimensions but deteriorates external dimensions. XCT voxel size scale error can be compensated by either the two-sphere calibration or the CMS normalization method. However, it is essential to ensure that these methods are based on an accurate reconstruction volume. The physical measurement results suggest that the deviation between XCT and CMS measurements of the rough cylinder part is mainly due to the mechanical filter effect of CMS, which is further confirmed by simulation measurements.

Keywords: Additive manufacturing, Dimensional metrology, X-ray Computed Tomography, Coordinate-measuring system, Simulation

1. Introduction

X-ray Computed Tomography (XCT) is a non-destructive imaging technique that enables the restoration of internal geometries. In comparison to well-established Coordinate Measuring Systems (CMS) technology, XCT offers the advantage of contactless evaluation of overall structures. Moreover, it remains unaffected by mechanical filtering effects on the surfaces of rough additive manufacturing (AM) components. However, despite its significant advantages in dimensional measurement, XCT still faces challenges in terms of traceability and reliable calibration, which are influenced by various factors such as XCT beam hardening and XCT voxel size scale error.

Regarding the study of XCT beam hardening, previous research conducted by Townsend et al. [1] revealed that beam hardening affects XCT measurements of the internal and external diameters of smooth cylinders. Where the internal diameter was underestimated and external diameter was overestimated. Through local iterative surface determination and global voxel size calibration, it was possible to reduce the disparity between XCT and CMS measurements to less than 1% for both internal and external diameters. Lifton et al. [2] investigation encompassed scattering and beam hardening in XCT simulation, which demonstrated that local iterative surface determination effectively mitigated scattering, but could not eliminate beam hardening errors. Furthermore, Yang et al. [3] highlighted that the reliability of different surface determination methods varies depending on the specific circumstances. To address this issue, Yang's study proposes the utilisation of a watershed algorithm to enhance robustness under beam hardening conditions.

Regarding the research on XCT voxel size scale error, there are various methods for determining the voxel size, with the most common one being based on the distance from the X-ray source to detector, and the distance from X-ray source to measurement object [4]. However, this method is often affected by temperature, drift effects, distance errors of source-object-detector, leading to voxel size scale error [5]. To address this, several correction methods are available, including spherical disk, computer-aided accuracy (CAA) database, and additional compensation strategies using CMS [4]–[6].

This study employs a combination of physical experimentation and simulation techniques to investigate the influence of beam hardening and voxel size on dimensional measurements in XCT. Specifically, a novel approach for correcting voxel size scale error is explored, obviating the need for an additional XCT scan and mitigating the effects of material differentiation. To facilitate accurate XCT and CMS simulations, a virtual part is synthesised using authentic AM surface data. Furthermore, the CMS simulation algorithm is enhanced by incorporating 2D morphological operations to account for the influence of neighbouring surface topography. Figure 1 shows the flowchart diagram of the general methodology.

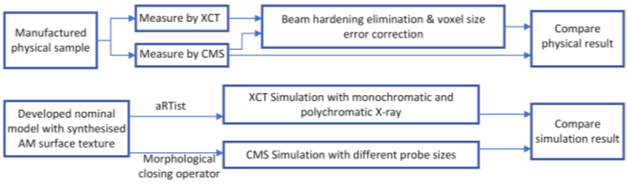


Figure 1. Outline of the proposed methodology.

2. Material and Methods

2.1. Manufacture of Physical Part

A hollow cylinder composed of 316L stainless steel powders was fabricated by selective laser melting (SLM) using a laser power of 110 W, a scan speed of 500 mm/s, a hatch spacing of 110 µm, and a layer thickness of 50 µm. Subsequently, half of the cylinder was subjected to surface treatment to achieve a smooth surface texture (see Figure 2 (a)-(c)). Given the negligible influence of mechanical filtering effects on CMS for such smooth surfaces, the dimensional measurements obtained from the smooth-half cylinder were employed as reference values for the computation of normalisation factors to standardise XCT measurements.

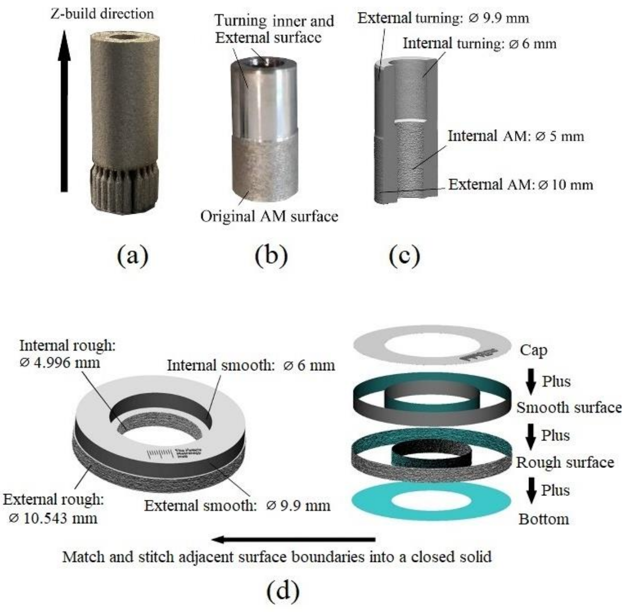


Figure 2. Hollow cylinder part: (a) raw sample; (b) sample with its half side turned into a smooth surface; (c) nominal dimensions of the design; (d) construction of the virtual sample.

2.2. Synthesis of the Virtual Part

The virtual sample was generated by synthesising planar surface data acquired using an Alicona G4 Focus Variation System (FVM) and subsequently transforming it into a cylindrical geometry. Moreover, smooth surfaces were incorporated into the virtual part to mimic the turned surfaces observed on the physical counterpart, as depicted in Figure 2 (d).

3. Physical and Simulation Measurement setup

3.1. Physical Measurement Setup

For the CMS measurements, a Zeiss Contura G2 HTG fitted with a VAST XXT 2 mm probe head was used to measure the test piece. The turned end was taken as the benchmark to measure the diameters at six depths on the cylinder (repeat measurement for each depth five times) (see Figure 3.).

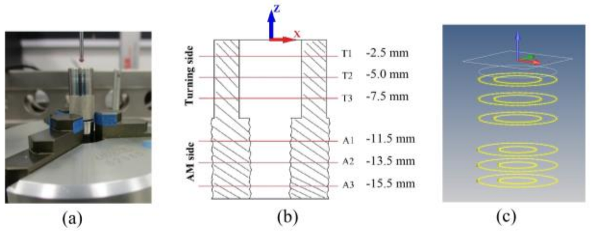


Figure 3. CMS measurement procedure: (a) physical artefact mounted in a three-jaw chuck; (b) different diameter measurement depths (including both internal and external surfaces); (c) 6 sets of cylinder circumference profile data (including both internal and external surfaces).

For the XCT measurements, three repeat measurements were conducted using a Nikon Metrology XCT H225M with voltage 150 kV, current 150 µA, 0.5 mm copper pre-filter, 3141 projection images and voxel size 20 µm. The data were reconstructed with three beam hardening correction strengths (1, 2, and 3), using the local iterative surface determination. Voxel size scale error was corrected using two separate approaches. In the first approach, NPL's two-sphere reference object was scanned to derive the centre-to-centre distance for global voxel size scale error [7]. And the second approach with CMS normalised for internal and external separate. Table 1 lists the nomenclature for XCT results.

Table 1 Nomenclature of different calibration types and different beam hardening elimination.

BHE **Voxel correction**	**BHE1**	**BHE2**	**BHE3**
Raw	BHE1 Raw	BHE2 Raw	BHE3 Raw
CMS Normalised	BHE1 Normalised	BHE2 Normalised	BHE3 Normalised
Two-sphere corrected	BHE1 Corrected	BHE2 Corrected	BHE3 Corrected

3.2. Simulation Measurement Setup

To simulate CMS measurements, a morphological closing/opening filter was applied to the corresponding circumference profiles of the virtual sample, utilising 2 mm probe tip diameters. The morphological closing/opening filter emulates the movement of a ball rolling, similar to the scanning motion of a CMS probe [7]. However, a limitation of performing morphological filter solely on the 2D circumference profiles is the lack of consideration for neighbouring surface topography.

To address this limitation, a compensation method is proposed to enable a 2D disk structuring element to achieve equivalent results to those obtained with a 3D sphere [8]. This method aims to capture sufficient surface topography data necessary for evaluating the interaction between the 3D probe tip and the surface. Refer to Figure 4 for a visual representation.

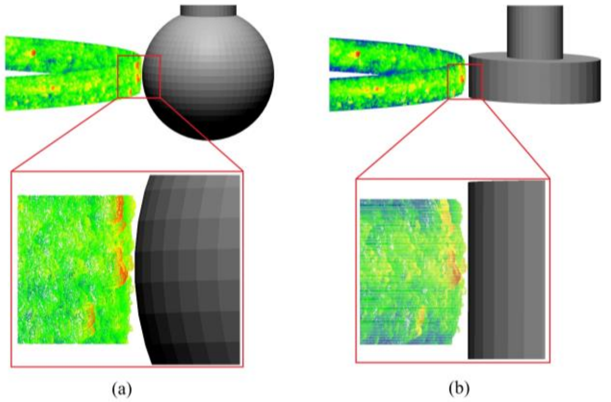


Figure 4. Deformation of sectioned ring surface: (a) surface section, sphere probe; (b) deformation of surface section, cylinder probe.

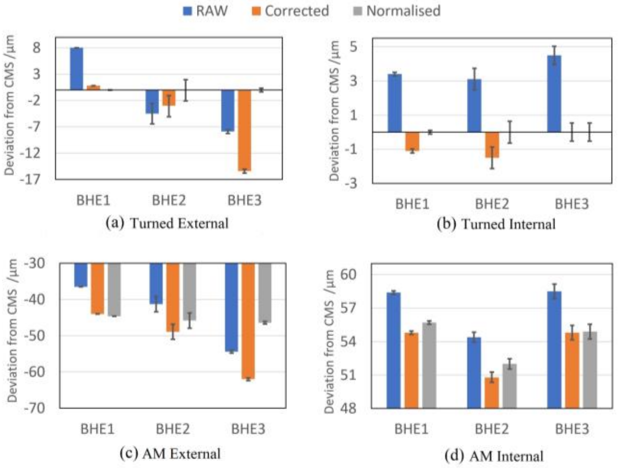
XCT scan is simulated by aRTist with: 316L stainless steel with density 8 kg/m^3, monochromatic and polychromatic X-ray, voltage 125 kV, current 1000 µA, no pre-filter, 3141 projections, point focal spot type, voxel size 20 µm, and local iterative surface determination.

4. Result and Discussion

4.1. Physical Measurement

It is noted that the internal diameter of the corrected data is almost the same as the CMS normalised result (presented in Figure 5(b)). This implies that the two-sphere correction with BHE3 applied reduced the voxel size scale error and beam hardening error on the measurement of internal diameters; however, a deviation of 15.4 µm is noticed on the external diameter. It is probably because the BHC provided by CT Pro is a global correction that applies to the internal and external surfaces. While the deviation of the internal geometry was reduced, more departures appeared for the external geometry. This is also evidenced in the BHE1 results. The deviation between the XCT corrected external diameter and the CMS diameter is only 0.8 µm, (refer to Figure 5 (a)), which indicates that the impact of beam hardening on external diameter is trivial. The results of BHE2 seem unexpected. For the external surface, the diameter deviation (3.0 µm) is larger than BHE1 (0.8 µm) but smaller than BHE3 (15.4 µm). However, for the internal diameter, the deviation of BHE2 (1.5 µm) is the largest after correction. It is speculated that BHE2 enhances noise without sufficiently reducing beam hardening image artefacts resulting in the observed increase in the deviation.

For the AM as-built surfaces, the XCT measurement results generated after the two-sphere correction and the CMS normalisation are close to the BHE1 external diameters and the BHE3 internal diameters, respectively. The difference between them is 0.6 µm and 0.1 µm, respectively, (refer to Figure 5 (b)). In all cases, larger deviations at tens of micrometres are observed between XCT and CMS measurements. This significant deviation can be attributed to the mechanical filtering effect of CMS.



(a) Turned External (b) Turned Internal

(c) AM External (d) AM Internal

Figure 5. Deviation of XCT measurement from CMS measurement in each region with repeatability error, (a) turned external; (b) turned internal; (c) AM external; (d) AM internal.

4.2. Simulation Measurement

Table 2 presents the internal and external cylinder diameters obtained from CMS and XCT simulations. While CMS measurements are unaffected by mechanical filtering on ideal smooth surfaces, the rough texture of the AM surface introduces substantial deviations. Specifically, the AM internal surface exhibits a significant deviation of 66.8 µm, while the external surface shows a deviation of 62.3 µm due to the mechanical filtering effect. In comparison, the deviations observed in the XCT simulation measurements are considerably smaller than those in CMS. Monochromatic X-ray simulation does not produce the beam hardening effect, resulting in minimal deviations for both the external and internal diameters, measuring only 2.6 µm and 2.9 µm, respectively. Conversely, when employing polychromatic X-ray simulation, a higher deviation is observed in the internal diameter (4.9 µm) compared to the external diameter (0.2 µm).

Table 2 Diameters resulting from 2 mm probe CMS and XCT simulation measurements of the AM as-built and smooth surface (Unit: µm).

	Smooth		**AM as-built**	
	Internal	**External**	**Internal**	**External**
Nominal	5989.3	9907.6	4926.2	10112.0
XCT Mono	5991.9 [+2.6]	9904.7 [-2.9]	4925.3 [-0.9]	10116.3 [+4.3]
XCT Poly	5994.2 [+4.9]	9907.8 [+0.2]	4925.1 [-1.1]	10115.4 [+3.4]
CMS	5989.3 [0]	9907.6 [0]	4859.4 [-66.8]	10174.3 [+62.3]
[]: difference from nominal				

5. Conclusion

To evaluate the dimensional measurement capabilities of XCT under different beam hardening elimination and voxel size scale error correction techniques, a comparative analysis was conducted by comparing XCT measurements with those obtained using CMS. This assessment involved examining physical and virtual hollow cylinder parts with AM and turned surface textures, the key findings of this investigation are presented below:

1. XCT can achieve comparable result to CMS for internal and external dimensions with smooth and rough surface textures in the correct data configuration.
2. Tactile CMS suffers from a significant mechanical filtering effect in the case of AM rough surface texture. The external diameter would overestimates, but underestimates the diameters of the internal diameter.
3. Beam hardening elimination could result in a more accurate determination of internal surfaces. However, it may also diminish the accuracy of external-surface determination (depending on the correction strength). Inappropriate correction strength can produce negatively affect results.

Future work will investigate more capable beam hardening elimination methods and surface determination which are expected to yield good results for both external and internal dimensions.

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References

[1] A. Townsend *et al.*, “An interlaboratory comparison of X-ray computed tomography measurement for texture and dimensional characterisation of additively manufactured parts,” *Addit Manuf*, vol. 23, pp. 422–432, Oct. 2018, doi: 10.1016/j.addma.2018.08.013.

[2] J. J. Lifton and S. Carmignato, "Simulating the influence of scatter and beam hardening in dimensional computed tomography," *Meas Sci Technol*, vol. 28, no. 10, 2017, doi: 10.1088/1361-6501/aa80b2.

[3] X. Yang, W. Sun, and C. L. Giusca, "An automated surface determination approach for computed tomography," *NDT and E International*, vol. 131, Oct. 2022, doi: 10.1016/j.ndteint.2022.102697.

[4] S. Carmignato, *Industrial X-Ray Computed Tomography*.

[5] P. Müller, J. Hiller, Y. Dai, J. L. Andreasen, H. N. Hansen, and L. De Chiffre, "Quantitative analysis of scaling error compensation methods in dimensional X-ray computed tomography," *CIRP J Manuf Sci Technol*, vol. 10, pp. 68–76, 2015, doi: 10.1016/j.cirpj.2015.04.004.

[6] W. Sun, S. Brown, and R. Leach, "NPL REPORT ENG 32 An overview of industrial X-ray computed tomography Sun W, Brown S B and Leach R K JANUARY 2012," *Measurement*, no. January, 2012.

[7] W. Sun, S. Brown, N. Flay, M. McCarthy, and J. McBride, "A reference sample for investigating the stability of the imaging system of x-ray computed tomography," *Meas Sci Technol*, vol. 27, no. 8, 2016, doi: 10.1088/0957-0233/27/8/085004.

[8] W. Liu, "Verification of x-ray computed tomography for additive manufacturing dimensional & surface texture metrology and deployment to internal geometry measurement," University of Huddersfield, 2022.