Reference standards for XCT measurements of additively manufactured parts

Anne-Françoise Obaton[1], Christopher Gottlieb Klingaa[2], Clément Rivet[1], Kamran Mohaghegh[3], Sina Baier[4], Jan Lasson Andreasen[5], Lorenzo Carli[5], Leonardo De Chiffre[2]

[1]LNE, 1 rue Gaston boissier 75015 Paris, France, e-mail: anne-francoise.obaton@lne.fr, clement.rivet@lne.fr

[2]DTU Mekanik, Produktionstorvet 425, 2800 Kgs. Lyngby, Denmark, e-mail: cgkli@mek.dtu.dk, ldch@mek.dtu.dk

[3]Metrologic ApS, Håndværkersvinget 10, 2970 Hørsholm, Denmark, e-mail: kam@metrologic.dk

[4]DTU Fysik, Fysikvej 311, 2800 Kgs. Lyngby, Denmark, e-mail: sbaier@fysik.dtu.dk

[5]Novo Nordisk A/S, Brennum Park 20K, 3400 Hillerød, Denmark, e-mail: jlsa@novonordisk.com, lzcl@novonordisk.com

Abstract
An increasing number of industrial sectors are considering the potential of additive manufacturing as an asset to improve their production. Indeed, additive manufacturing enables the fabrication of very complex geometries and inner cavities that cannot be manufactured with conventional techniques. However, in critical sectors such as aerospace, defence and medical, the parts need to be certified, which requires parts to be non-destructively characterised in terms of flaws, geometry and dimensional accuracy. X-ray computed tomography is the only current 3D volumetric technique, which is suited for the non-destructive analysis of internal flaws, geometry and measurements of internal dimensions and roughness. However, regardless of its huge potential, X-ray computed tomography is not as mature a technology for dimensional metrology as compared to conventional tactile coordinate measuring machines. In most cases there is no traceability to SI units in the dimensional domain. Recently, numerous reference standards (i.e. physical artefacts) addressing X-ray computed tomography dimensional accuracy have been published, but they do not necessarily address the calibration of XCT system in connection with AM parts. In this work, a new and improved standard in three different materials has been designed with a dual purpose: Fully calibrating X-ray computed tomography for dimensional measurements while being representative of additively manufactured parts in terms of flaws and material, meeting the needs of the industry. These standards will be used to metrologically validate X-ray computed tomography for the inspection of additively manufactured parts.

Keywords: X-ray computed tomography (XCT), dimensional metrology, reference standards, additive manufacturing

1 Introduction

Additive manufacturing (AM) is a promising manufacturing method, which enables the production of very complex parts with inner cavities. This advantage as well as several others such as on-demand mass production of customized parts, are very attractive for the aerospace, defense and medical sectors. However, in such critical sectors, the integrity of the fabricated AM parts needs to be ensured in order for these parts to be certified. This requires quality control methods, including non-destructive testing (NDT), to be implemented and particularly volumetric NDT to inspect both internal and external features of the parts. At the present time, the most powerful volumetric method in term of inspection capability is X-ray computed tomography (XCT). Indeed, it enables a volumetric visualization giving indications of flaws in the part, but also enables geometrical deviations of the part from its nominal geometry to be determined (comparison between nominal geometry and model obtained with XCT). Furthermore, dimensional measurements can also be performed on the 3D XCT volume. However, XCT lacks traceability and the uncertainties on dimensional measurements using XCT have to be evaluated.

In order to characterise XCT to perform dimensional measurements, several standards have been manufactured by different institutions all over the world. However, a lot of these standards aim at calibrating XCT regarding only one of its specificities and are not representative of AM parts.

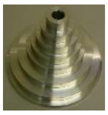
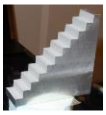
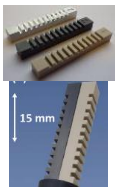
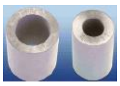
In this paper, a new reference standard has been designed and manufactured in three different materials taking into account the typical AM characteristics (types of flaws and material) and attempts to calibrate several XCT specificities simultaneously. Thus, it combines several measurable features in a single standard dedicated to XCT dimensional calibration, as well as XCT scanning of AM parts.

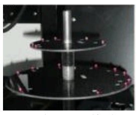
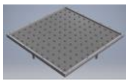
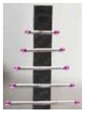
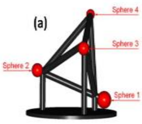
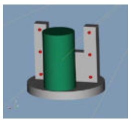
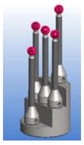
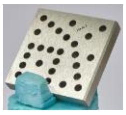
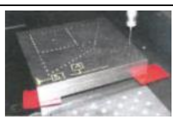
First, a list of XCT existing standards are presented. Second, the design (shape, dimensions, and materials), aim, fabrication and metrological characterisation conducted using a coordinate measuring machine (CMM) of the standards are presented, as well as some preliminary XCT scans using commercial tomographs.

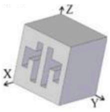
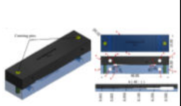
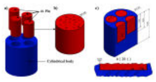
2 Existing standards

In order to design an appropriate multi-functional standard for XCT metrological calibration, dedicated to AM, first a list of existing standards for XCT measurements was compiled (Table 1).

Table 1: Existing XCT standards for dimensional measurements [1]–[23].

Standard	Manufacturer	Material	Dimension (mm)	Standard	Manufacturer	Material	Dimension (mm)
 Step cylinder	Empa, Switzerland	Aluminium	∅40, 60, 80, 100, 120, 160, 200, 220 H: 160 Hole: ∅20	 Multi-wave standard	Florianópolis , Brazil	Structural aluminum league (ASTM 2024-T3).	$\varnothing_{Ext}$40 $\varnothing_{Int}$22 H30
 Step cylinder gauge with a central bore hole	NMIJ, Japan	Lead-free MgSi aluminium alloys	$\varnothing_{max}$50 central hole ∅8	 Mini cylinder head	BAM, Germany	-	-
 Step cylinder	DTU, Denmark	POM	largest outer Ø17.5 inner Ø3	 Mutli-sphere standard	METAS, Switzerland	Zerodur (Z) or Al or CFRP cylinders+17 steel (S) spheres	Al 25H20.1 CFRP Ø26.8H21 ZØ28,H23.2 14 S spheres Ø1, 3 S spheres Ø1.5
 Step pyramide	Empa, Switzerland	Aluminium	160×160×40	 Miniaturized single cylinder head	PTB, Germany	Aluminium	90×90×90
 Step wedge	DTU, Denmark	Aluminium	11 steps H6	 Multi-material ring	PTB and BAM, Germany	Titanium, Aluminium, Steel, Brass, Polymer (Trovidur)	$\varnothing_{max}$25
 Multi-material hole cube	PTB, Germany	Aluminium and titanium or aluminium and cesic or cesic and titanium	30×30×30 17 holes ∅4	 Cylindrical multi-material assembly	DTU, Denmark	PEHD 500 and PP-H	∅7.5 H10
 Step gauge	DTU, Denmark	Aluminium 2011 or PPS or PEEK or bis-acryl or bi-material PEEK/PPS	L60 11 grooves l3.50	 Hollow cylinder	PTB, Germany	Aluminium	∅30
 Cylindrical step gauge in a tube	DTU, Denmark	Aluminium inside a glass tube	Tube L60 gauge L56 6 grooves l3.50	 QFM Cylinder	University of Erlangen, Germany	Titanium	H80 $\varnothing_{out}$ 50 $\varnothing_{in}$ 40
 CT Tube	DTU, Denmark	Ruby spheres on carbon fiber tube	Spheres Ø8	 Pan flute standard	University of Padova, Italy	Glass tubes on a carbon fibre frame	2.5 to 12.5

Standard	Manufacturer	Material	Dimension (mm)	Standard	Manufacturer	Material	Dimension (mm)
 Micro sphere tetrahedron	BAM, Germany	Ruby balls on a pyramidal polystyrene holder	Ø14.29	 Ball-bar	PTB, Germany	Ceramic balls on a carbon fibre	L300
 Micro sphere tetrahedron	PTB, Germany	Ruby ball on an amorphous carbon shaft	Ø0.5 - 3	 Sphere disk	Nikon	CFRP+ruby sphere	Larger disk 160
 Micro sphere tetrahedron	PTB, Germany	Ruby	∅0.5 or 3	 Ball plate	DTU, Denmark	Ruby spheres on carbon fibre plate	Plate 55×55 sphere ∅5 pitch 10
 Mini star probe	PTB, Germany	Carbon fiber reinforced polymer (CFRP) and ruby spheres	Horizontal distance between the spheres 10	 Ball Plate	METAS, Switzerland	Aluminium substrate+121 steel spheres	400×400 spheres Ø10
 CT tree	DTU, Denmark	Carbon fiber reinforced polymer (CFRP) + ruby balls	Fibers 16 to 40 balls ∅3	 Gauge	Yxlon, Germany	Carbon fiber plates or boron nitrite+ruby spheres	The spheres form a square of 16 nominal edge length
 CT Tetrahedron	University of Padova, Italy	Ruby and carbon fiber frame	Spheres ∅ 5, 4, 3 carbon fiber ∅2	 Multi matérial standard	Yxlon, Germany	Ruby spheres	-
 Probe forest	VTT, Finland	Steel+carbon fiber+ruby spheres	Distance A-E 33 Sphere ∅ 6	 Hole plate	NMIJ, Japan and PTB, Germany	Aluminium or steel	Plate 6×6×1 or 48×48×8 28 holes ∅4
 Forest Gauge	NMIJ, Japan	-	-	 Hole plate	Empa, Switzerland	Steel	144×144×24
 Multi sphere standard	Zeiss	Ruby spheres+ ceramic or CFRP shafts	Several sizes	 Hole plate	VTT, Finland	Aluminium or steel	4 sizes 6, 10, 20, 50 mm Hole Ø0.6, 1, 2, 5
 Multi-material sphere	PTB, Germany	Al_2O_3 (white)/Si_3N_4 (black)	∅10	 Printed circuit board	PTB, Germany	Invar foilswith hole grid	Thickness 50 µm, 7.5 ×7.5 15 ×15 30 ×30
 Spheres of different diameters	Technological Center AIMEN, Spain	Ruby	L20 ∅10, ∅9, ∅8	 Fibre gauge	University of Padova, Italy	Glass Fibres	12 fibres ∅125 L350 to 700 µm

Standard	Manufacturer	Material	Dimension (mm)	Standard	Manufacturer	Material	Dimension (mm)
 Spherical calotte plate	PTB, Germany	Zerodur	20×20×4.5	 Hyperbolic paraboloid	CMI and CTU, Czech republic	Titanium or polymer	30×30×15
 Spherical calotte cube	PTB, Germany	Titanium	cube 10×10×10 5×5 calottes ∅0.8	 Spatial hyperbolic paraboloid	CMI, Czech republic	Certal (AlZn5MG3Cu)	100×100×100
 Cactus step Gauge standard	KU Leuven, Belgium	Aluminium	45×45×45	 Threaded tube	DTU, Denmark	Brass and nickel	L46.4 ∅4.1
 Gap standard	PTB, Germany and University of Padova, Italy	Aluminium and titanium or aluminium and cesic	Gap 500 µm to 0 µm, step 10 µm to 1000 µm	 Reference object with artificial porosities	University of Padova, Italy	Aluminium	Ø15 Body H15 or H23 4 removable cylindrical pins Ø5
 Corner cube standard	METAS, Switzerland	Quartz glass+ruby spheres or silicon-nitride (SiN) spheres	Ruby ∅14.7 H 10.2, sphere Ø 1 SiN Ø 8, height 6.1, sphere Ø 0.4				

The aims of the standards, considering their shape and features, are summarized in Table 2.

Table 2: Aims of the standards according to their shape and features.

Standard shape and features	Aims
Step cylinders and step wedges	• External geometrical measurement error • Scale factor correction • Maximal penetration thickness (contrast) • Beam hardening correction • Optimization of a threshold value
Step cylinders with a central or stepped bore hole inside	• Internal geometrical measurement error • Scale factor correction • Optimization of a threshold value
Hollow cylinders	• Scale factor correction • Form error
External spheres, calottes, cylinders	• Scale factor correction • Length measurement error • Form error • CT machine geometry determination
Ball plate	• Flat-panel detector distortion correction
Corner cubes with spheres	• Measurement – simulation comparisons and Simulation validations
Free form	• Free form capability measurement
External groove	• Spatial resolution
Internal geometry	• Defect detection

3 Design of the standards

3.1 Shape of the standards

Considering the existing standards (Table 1), to reach our purpose to design a standard covering several specificities of XCT for its calibration while being dedicated to AM parts, it was decided that the three standards in different materials would have the same nominal shape (see Figure 1): A monoblock A consisting of five stacked cylinders of different diameters (step cylinder) with a through central hole. Thirty three sphere calottes B, with identical diameters, are evenly distributed on the five steps. Around the central hole, four holes of different depths for removable cylindrical plugs C containing inner counterbores are drilled and four calottes D of different diameters are placed on the top of the plugs. Furthermore, four removable inserts E with two external grooves are part of the standard.

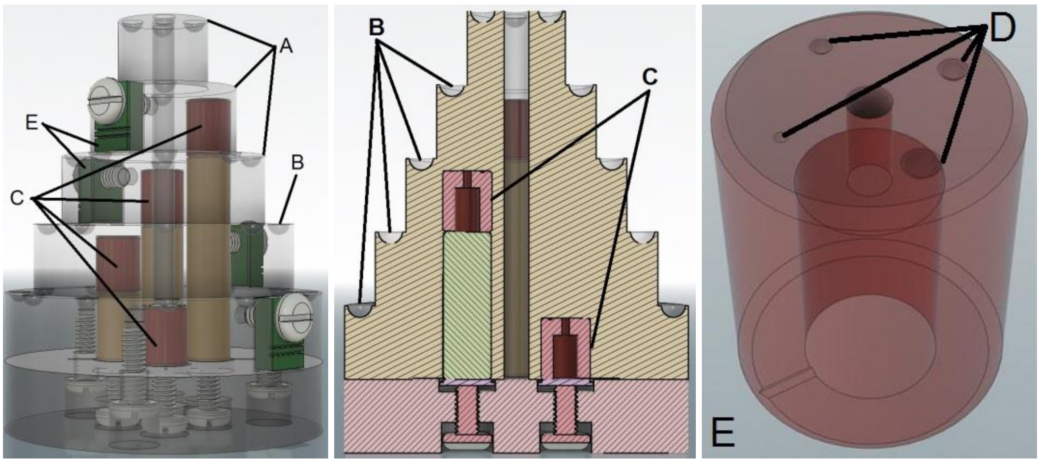


Figure 1: Geometrical shape of the new standard.

3.2 Dimensions of the standard

The dimensions of the standard are given in Figure 2.

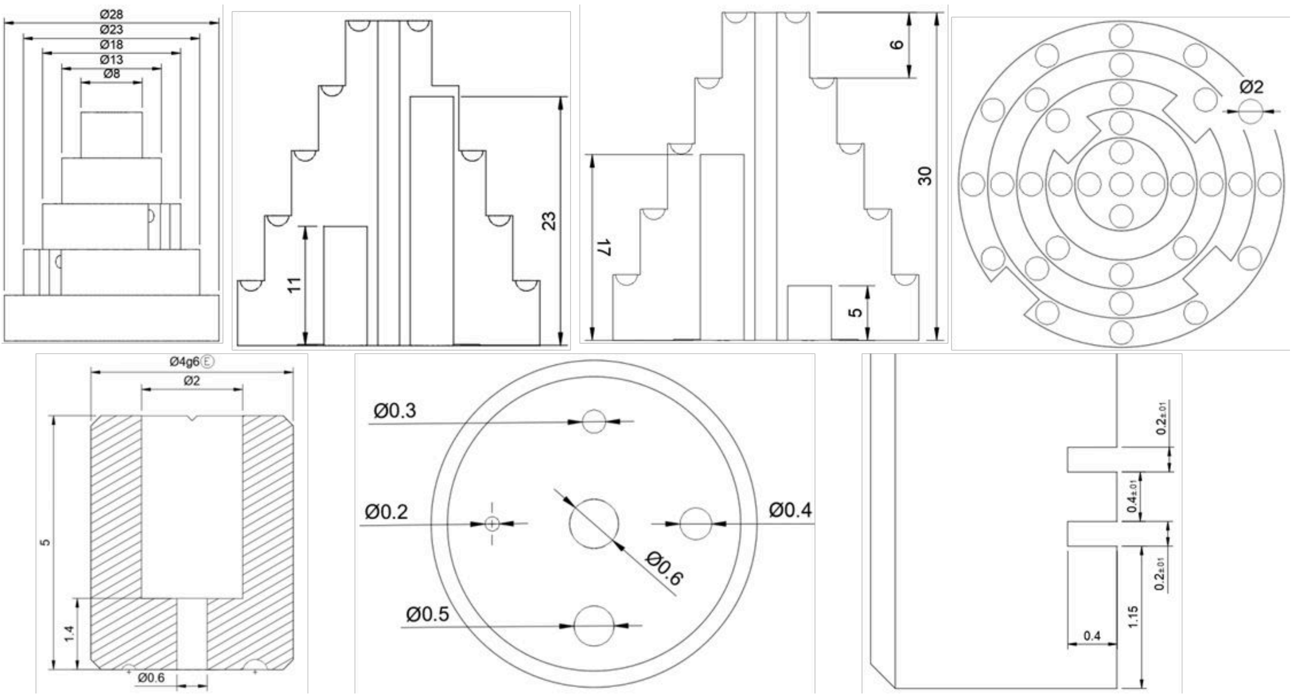


Figure 2: Dimensions of the new standard. Top: side and top views of the global shape. Bottom left: side view of the internal plug. Bottom center: top view of the internal plug. Bottom right: side view of the external insert.

3.3 Materials of the standards

There are several materials that are used in AM such as polymers, ceramics and metals. Considering our interactions with the industry, polymers and metals were prioritized, more specifically, acrylonitrile butadiene styrene (ABS) which has proven to be stable [24], stainless steel and aluminium, three materials commonly used in AM.

As the shape and size of the standard in the three different materials are identical, the internal plugs and external inserts are switchwable from one global shape to another in a different material. This is not of particularly interest for AM at the present time, but it is meant being relevant for the metrological characterisation of XCT systems with regards to multimaterial parts.

4 Aim of the standards

Compared to the already available XCT standards (Table 1), the proposed standard is multi-functional and specifically dedicated to XCT performing scans on AM parts. It allows for the calibration of XCT regarding several specificities simultaneously and to detect internal metrological features down to 200 to 600 µm. The fact that it combines several different measurable features in a single standard allows a considerable reduction of the scanning time to qualify a XCT. Indeed, instead of scanning several standards with different purposes, this one is a multi-purpose standard. The features of the standard and their metrological purposes are listed below:

- The step cylinders are suitable to detect the maximum possible material thickness which can be penetrated by a given XCT system, including multi-material evaluation, thus to evaluate the contrast resolution of the XCT for different thicknesses.
- The internal plugs with sphere calottes, of different diameters, on their top allow for evaluating the capability of XCT to detect internal features in a mono- or multi-material part such as porosities, which are common flaws in AM [9]. These plugs can be examined at different material thicknesses, which enables the evaluation of the ability of the XCT to detect tiny features for different thicknesses.
- The inner counterbores allow for diameter and form error of internal holes to be evaluated.
- The external grooves enable the structural resolution of the XCT to be evaluated.
- Finally, the sphere calottes evenly distributed on each step allow the determination of the scale factor as well as the length measurement error.

5 Fabrication of the standards

Removable plugs with inner counterbores and inserts with external grooves allow easier manufacturing of the standards.

The global shapes of the standards have been machined at DTU Mekanik on a Mikron UCP 600, and the plugs and inserts on a Mikron HSM 400 U LP, both from AgieCharmilles (Figure 3).

Figure 3: Stainless steel standard (left), plug with inner counterbore and sphere calottes on the top (center), insert with external grooves (right).

6 Metrological qualification of the standards

The standards have been designed in such a way that they can be fully qualified with a CMM, as well as with XCT. Indeed, the plugs with inner counterbores and inserts with external grooves are removable to allow metrological calibration with CMM. Thus, when assembled, the plugs allow measurements of inner metrological calibrated features.

6.1 Measurand selection

The following measurands have been selected:

1. The position of the center of the thirty-three spheres, which fit the calottes, evenly distributed on each step, to enable dimensional measurements between calottes (Figure 4a).
2. The width of each groove and the distance between the two grooves measured at the surface and at the middle length of the grooves (Figure 4b).
3. The diameter of the sphere fitting the porosities on the top of the plug (Figure 4c).

4. The diameter, roundness and centre of the circles fitting the 0.6 mm inner counterbore in the plug at different heights from the surface: 0.1, 0.4, 0.7 and 1.3 mm (Figure 4d).

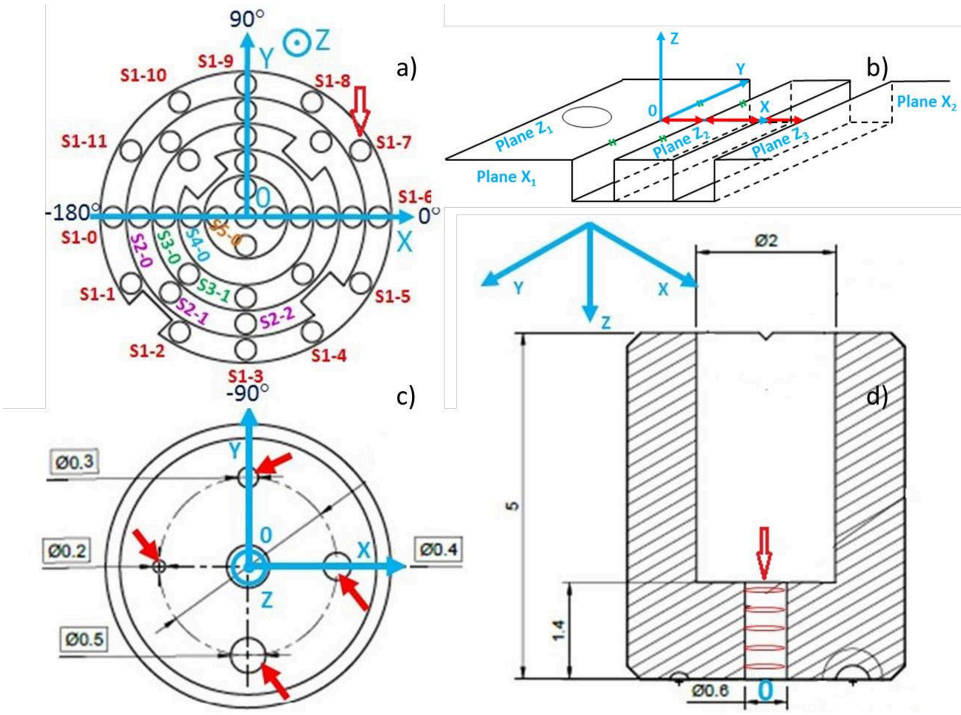


Figure 4: Schematic representation of the measurands indicated by the red arrows. a) Top view of the standard with the thirty-three spheres calottes. b) Side view of the insert with two external grooves. c) Top view of the plug with the four sphere calottes. d) Side view of the plug with the inner counterbores.

6.2 Metrological characterisation of the standards

A Zeiss Prismo CMM (Figure 5 left) was used for the metrological characterisation of the global shape, the internal plugs and the external inserts at DTU Mekanik, and then a Zeiss Accura II CMM (Figure 5 right) will be used at LNE for comparison.

Figure 5: Zeiss Prismo CMM (left) at DTU Mekanik and Zeiss Accura II (right) CMM at LNE.

7 XCT characterisation of the standards

A comparison campaign of XCT machines with these reference standards will be organized in the frame of the European project "AdvanCT" (Computed Tomography for dimensional and surface measurements in industry) which has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme. The purpose of the interlaboratory comparison is to investigate the performance of industrial CT with respect to dimensional measurements for traceability, more specifically for quality control of AM parts.

The first scans have been performed at DTU Fysik on the stainless steel (SS) global shape using a Nikon XT H 225 ST, while a Zeiss Xradia Versa 410 was used to scan the ABS global shape. Scans of the ABS global shape will also be performed using a Werth Tomoscope XS XCT scanner at DTU Mekanik. Finally, the standards will be sent to other countries for measurements.

The Nikon XT H 225 ST microfocus XCT is composed of a source with a maximal voltage of 225 kV, a maximal power of 225 W and focal spot sizes from ca. 3 µm to 225 µW, dependent on the used target geometry and power. A tungsten target in reflection mode was used for the scans. The Zeiss Xradia Versa 410 is composed of a source with a voltage ranging between 40 and 150 kV and with a maximal power of 10 W. The system has a set of different objectives of which the Large Field of View (LFOV) objective was used for the scans.

The set up of the standards inside the XCT are presented in Figure 6 whereas the scanning settings are provided in Table 3 and Table 4. The XCT images of the standards shown in Figures 7 and 8 enable to see the internal inserts in ABS in ABS global shape at the higher thickness of the standards, but also in the SS global shape, in other words in the case of multi-material standard. However, in the case of multi-material standard, the image resolution might not be sufficient to perform dimensional measurements. Nevertheless, it is high enough to perform dimensional measurements of all the defined measurands in the case of the mono-material standards.

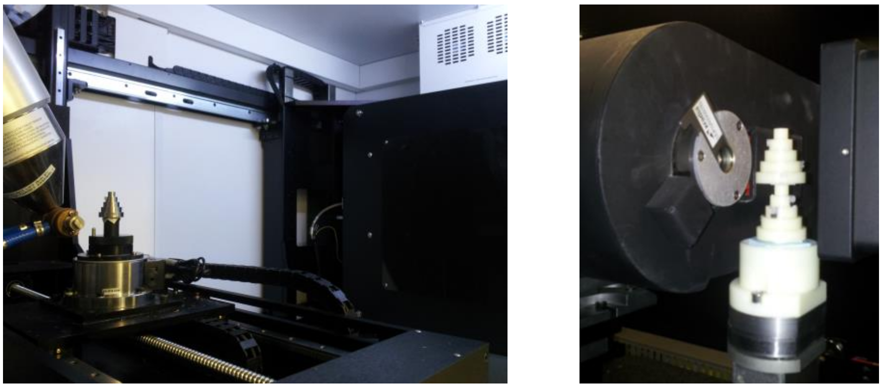


Figure 6: Set up of the stainless steel global shape in the Nikon XT H 225 ST (left) and of the ABS global shape in the Zeiss Xradia Versa 410 (right).

Table 3: Scanning settings used for the stainless steel (SS) global shape with ABS plugs and either ABS, SS or aluminium inserts with the Nikon XT H 225 ST.

Voltage (kV)	Power (W)	Exposure time (s)	Filter	Number of projections	Number of frames per projection	Binning	Scan duration	Reconstructed voxel size (µm^3)
220	20	2.8	1 mm Sn	1571	8	2x2	12 h 21 min	36.0×36.0×36.0

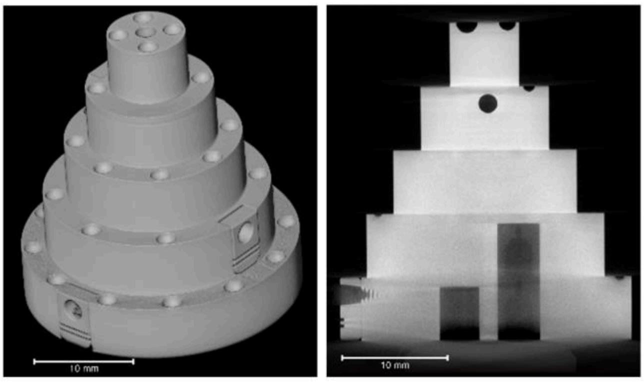


Figure 7: Nikon XT H 225 ST images of the SS global shape with SS external inserts and ABS internal plugs.

Table 4: Scanning settings used for the ABS global shape with ABS plugs and either ABS or SS inserts with the Zeiss Xradia Versa 410.

Insert material	Voltage (kV)	Power (W)	Exposure time (s)	Filter	Number of projections	Binning	Scan duration	Reconstructed voxel size (µm^3)
ABS	40	10	9	LE1	3201	1x1	9h 26min	19.36×19.36×19.36
SS	120	10	5	LE1	3201	1x1	6h 42min	19.36×19.36×19.36
SS zoom	140	10	52	LE1	3201	1x1	49h 26min	5.65×5.65×5.65

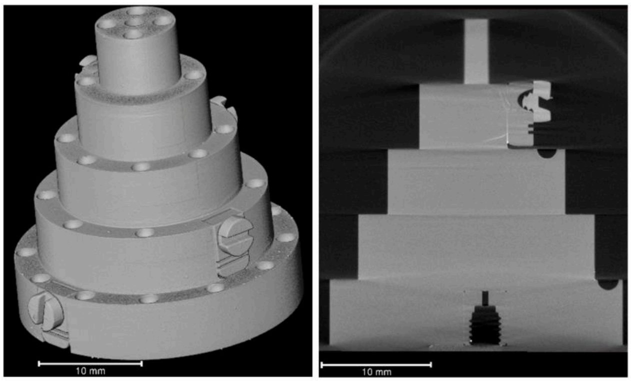


Figure 8: Zeiss Xradia Versa 410 images of the ABS global shape with ABS external inserts and ABS internal plugs.

8 Conclusions and future work

A compilation of existing X-ray computed tomography (XCT) standards for dimensional measurements was presented as well as their aims correlated to their shape and features. Considering this compilation, the design of new standards was defined (shape, dimensions and materials) to reach the goal we set out to achieve: Fully calibrating XCT for dimensional measurements being representative of additively manufactured (AM) parts in terms of flaws and material used in AM in critical industrial sectors. It was decided to fabricate standards with the same shape and dimensions in three different materials: ABS, stainless steel and aluminium. Furthermore, these standards have removable internal plugs and external inserts enabling multi-material combinations. The measurands were selected before the metrological qualification of the manufactured standards with a coordinate measuring machine (CMM). Preliminary XCT scans of the standards were performed, which are highly satisfactory. The following steps will be to realize measurements on the XCT images and to start the comparison campaign of XCT machines.

Acknowledgements

The authors would like to thank Claus Bremer and Søren Hansen from DTU Mekanik for the fabrication of the standards. The authors are also very grateful to Klaus Liltorp from DTU Mekanik and to Arthur De Soete from LNE for their contribution in CMM calibration and in providing the images respectively. Sina Baier is grateful for financial support from Innovation Fund Denmark [grant no. 5152-00005B] and the 3D Imaging Center at The Technical University of Denmark is gratefully acknowledged for their support on X-ray computed tomography acquisition and evaluation. This work was supported by the EMPIR programme, co-financed by the Participating States and from the European Union's Horizon2020 research and innovation programme.

References

[1] F. Arenhart, V. Camargo Nardelli, G. Donatelli, M. Porath, C. Isenberg, et R. Schmitt, « Design of a Multi-Wave Standard to Evaluate the Frequency Response of CT Measuring Systems », 2013.

[2] M. Bartscher, J. Illemann, et U. Neuschaefer-Rube, « ISO test survey on material influence in dimensional computed tomography », *Case Stud. Nondestruct. Test. Eval.*, vol. 6, avr. 2016.

[3] B. A. Bircher, F. Meli, A. Küng, et R. Thalmann, « CT geometry determination using individual radiographs of calibrated multi-sphere standards », 2019.

[4] A. Cantatore, J. A. B. Angel, et L. D. Chiffre, « Material investigation for manufacturing of reference step gauges for CT scanning verification », in *Proceedings of the 12th euspen International Conference*, 2012.

[5] S. Carmignato, W. Dewulf, et R. Leach, *Industrial X-Ray Computed Tomography*. Springer, 2017.

[6] S. Carmignato, D. Dreossi, L. Mancini, F. Marinello, G. Tromba, et E. Savio, « Testing of x-ray microtomography systems using a traceable geometrical standard », 2009.

[7] L. De Chiffre *et al.*, « Centre for Industrial Application of CT scanning (CIA-CT)–Four years of results 2009-2013 », 2014.

[8] P. Hermanek et S. Carmignato, « Reference object for evaluating the accuracy of porosity measurements by X-ray computed tomography », *Case Stud. Nondestruct. Test. Eval.*, vol. 6, p. 122‑127, nov. 2016.

[9] P. Hermanek et S. Carmignato, « Porosity measurements by X-ray computed tomography: Accuracy evaluation using a calibrated object », *Precis. Eng.*, vol. C, nº 49, p. 377‑387, 2017.

[10] U. Hilpert, M. Bartscher, M. Neugebauer, J. Goebbels, G. Weidemann, et C. Bellon, « Simulation-aided computed tomography (CT) for dimensional measurements », 2007.

[11] K. Kiekens *et al.*, « A test object with parallel grooves for calibration and accuracy assessment of industrial computed tomography (CT) metrology », *Meas. Sci. Technol.*, vol. 22, nº 11, p. 115502, sept. 2011.

[12] J.-P. Kruth, M. Bartscher, S. Carmignato, R. Schmitt, L. D. Chiffre, et A. Weckenmann, « Computed tomography for dimensional metrology », 2011.
[13] I. Linkeová, P. Skalník, et V. Zelenỳ, « Calibrated CAD model of freeform standard », in *Proc. XXI IMEKO World Congress "Measurement in Research and Industry*, 2015.
[14] M. Lüthi, B. A. Bircher, F. Meli, A. Kueng, et R. Thalmann, « X-ray flat-panel detector geometry correction to improve dimensional computed tomography measurements », *Meas. Sci. Technol.*, 2019.
[15] F. B. de Oliveira, M. Bartscher, et U. Neuschaefer-Rube, « Analysis of Combined Probing Measurement Error and Length Measurement Error Test for Acceptance Testing in Dimensional Computed Tomography », 2015.
[16] F. B. de Oliveira, A. Stolfi, M. Bartscher, et M. Neugebauer, « Creating a Multi-material Probing Error Test for the Acceptance Testing of Dimensional Computed Tomography Systems », 2017.
[17] A. Staude *et al.*, « Quantification of the capability of micro-CT to detect defects in castings using a new test piece and a voxel-based comparison method », 2011.
[18] A. Stolfi et L. De Chiffre, « 3D artefact for concurrent scale calibration in Computed Tomography », *CIRP Ann.*, vol. 65, nº 1, p. 499–502, 2016.
[19] A. Stolfi et L. De Chiffre, « Selection of items for "InteraqCT Comparison on Assemblies" », in *6th Conference on Industrial Computed Tomography*, 2016.
[20] A. Stolfi et L. De Chiffre, « Interlaboratory comparison of a physical and a virtual assembly measured by CT », *Precis. Eng.*, vol. 51, p. 263–270, 2018.
[21] T. Takatsuji, M. Abe, et H. Fujimoto, « Dimensional X-ray CT in Japan , development , application and standardization », 2014.
[22] F. Welkenhuyzen *et al.*, « Industrial Computer Tomography for Dimensional 2 Metrology : Overview of Influence Factors and 3 Improvement Strategies 4 5 6 », 2010.
[23] Zelený, Linkeová, et Skalník, « Calibration of freeform standard », *euspen*. .
[24] J. Angel et L. De Chiffre, « Comparison on Computed Tomography using industrial items », *CIRP Ann.*, vol. 63, nº 1, p. 473-476, janv. 2014.