Reference standards for XCT measurements of additively manufactured parts

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Reference standards for XCT measurements of additively manufactured parts

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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>
<thead>
<tr>
<th>Standard</th>
<th>Manufacturer</th>
<th>Material</th>
<th>Dimension (mm)</th>
<th>Standard</th>
<th>Manufacturer</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step cylinder</td>
<td>Empa, Switzerland</td>
<td>Aluminium</td>
<td>40, 60, 80, 100, 120, 160, 200, 220 H: 160 Hole: 20</td>
<td>Multi-wave standard</td>
<td>Florianópolis, Brazil</td>
<td>Structural aluminum league (ASTM 2024-T3).</td>
</tr>
<tr>
<td>Step cylinder gauge with a central bore hole</td>
<td>NMIJ, Japan</td>
<td>Lead-free MgSi aluminium alloys</td>
<td>50 central hole 28</td>
<td>Mini cylinder head</td>
<td>BAM, Germany</td>
<td>-</td>
</tr>
<tr>
<td>Step cylinder</td>
<td>DTU, Denmark</td>
<td>POM</td>
<td>largest outer Ø17.5 inner Ø3</td>
<td>Multi-sphere standard</td>
<td>METAS, Switzerland</td>
<td>Zerodur (Z) or Al or CFRP cylinders+17 steel (S) spheres</td>
</tr>
<tr>
<td>Step pyramide</td>
<td>Empa, Switzerland</td>
<td>Aluminium</td>
<td>160×160×40</td>
<td>Miniaturized single cylinder head</td>
<td>PTB, Germany</td>
<td>Aluminium 90x90x90</td>
</tr>
<tr>
<td>Step wedge</td>
<td>DTU, Denmark</td>
<td>Aluminium</td>
<td>11 steps H6</td>
<td>Multi-material ring</td>
<td>PTB and BAM, Germany</td>
<td>Titanium, Aluminium, Steel, Brass, Polymer (Trovidur)</td>
</tr>
<tr>
<td>Step gauge</td>
<td>PTB, Germany</td>
<td>Aluminium and cesium or cesic or cenic or cenic and titanium</td>
<td>30x30x30 17 holes 4</td>
<td>Cylindrical multi-material assembly</td>
<td>DTU, Denmark</td>
<td>PEHD 500 and PP-H</td>
</tr>
<tr>
<td>Multi-material hole cube</td>
<td>DTU, Denmark</td>
<td>Aluminium 2011 or PPS or PEEK or bis-acryl or bi-material PEEK/PPS</td>
<td>L60 11 grooves 13.50</td>
<td>Hollow cylinder</td>
<td>PTB, Germany</td>
<td>Aluminium 30</td>
</tr>
<tr>
<td>Multi-material</td>
<td>DTU, Denmark</td>
<td>Aluminium inside a glass tube</td>
<td>Tube L60 gauge L56 6 grooves 13.50</td>
<td>QFM Cylinder</td>
<td>University of Erlangen, Germany</td>
<td>Titanium H80</td>
</tr>
<tr>
<td>Cylindrical step gauge in a tube</td>
<td>DTU, Denmark</td>
<td>Ruby spheres on carbon fiber tube</td>
<td>Spheres Ø8</td>
<td>Pan flute standard</td>
<td>University of Padova, Italy</td>
<td>Glass tubes on a carbon fibre frame</td>
</tr>
<tr>
<td>CT Tube</td>
<td>DTU, Denmark</td>
<td>Glass tubes on a carbon fibre frame</td>
<td>2.5 to 12.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Standard</td>
<td>Manufacturer</td>
<td>Material</td>
<td>Dimension (mm)</td>
<td>Standard</td>
<td>Manufacturer</td>
<td>Material</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------</td>
<td>---------------------------------------------------------------------------</td>
<td>----------------</td>
<td>--------------------------</td>
<td>--------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Micro sphere tetrahedron</td>
<td>BAM, Germany</td>
<td>Ruby balls on a pyramidal polystyrene holder</td>
<td>Ø14.29</td>
<td>Ball-bar</td>
<td>PTB, Germany</td>
<td>Ceramic balls on a carbon fibre</td>
</tr>
<tr>
<td>Micro sphere tetrahedron</td>
<td>PTB, Germany</td>
<td>Ruby ball on an amorphous carbon shaft</td>
<td>Ø0.5 - 3</td>
<td>Nikon</td>
<td>CFPR+ruby sphere</td>
<td>Larger disk 160</td>
</tr>
<tr>
<td>Micro sphere tetrahedron</td>
<td>PTB, Germany</td>
<td>Ruby</td>
<td>Ø2.0 or 3</td>
<td>Ball plate</td>
<td>Yxlon, Germany</td>
<td>Carbon fiber plates or boron nitrite+ruby spheres</td>
</tr>
<tr>
<td>Mini star probe</td>
<td>DTU, Denmark</td>
<td>Carbon fiber reinforced polymer (CFRP) + ruby spheres</td>
<td>Horizontal distance between the spheres 10</td>
<td>METAS, Switzerland</td>
<td>Aluminium substrate+121 steel spheres</td>
<td>400x400 spheres Ø10</td>
</tr>
<tr>
<td>CT tree</td>
<td>University of Padova, Italy</td>
<td>Ruby and carbon fiber frame</td>
<td>Fibers 16 to 40 balls Ø2/3</td>
<td>Yxlon, Germany</td>
<td>Carbon fiber plates or boron nitrite+ruby spheres</td>
<td>The spheres form a square of 16 nominal edge length</td>
</tr>
<tr>
<td>CT Tetrahedron</td>
<td>VTT, Finland</td>
<td>Steel+carbon fiber+ruby spheres</td>
<td>Distance A-E 33 Sphere Ø 6</td>
<td>NMII, Japan and PTB, Germany</td>
<td>Aluminium or steel</td>
<td>Plate 6x601 or 48x48x8 28 holes Ø4</td>
</tr>
<tr>
<td>Probe forest</td>
<td>NMIJ, Japan</td>
<td>-</td>
<td>-</td>
<td>Empa, Switzerland</td>
<td>Steel</td>
<td>144x144x24</td>
</tr>
<tr>
<td>Forest Gauge</td>
<td>Zeiss</td>
<td>Ruby spheres+ceramic or CFRP shaft</td>
<td>Several sizes</td>
<td>VTT, Finland</td>
<td>Aluminium or steel</td>
<td>4 sizes 6, 10, 20, 50 mm Hole Ø0.6, 1, 2, 5</td>
</tr>
<tr>
<td>Multi sphere standard</td>
<td>PTB, Germany</td>
<td>Al₂O₃ (white)/Si₃N₄ (black)</td>
<td>Ø10</td>
<td>Printed circuit board</td>
<td>PTB, Germany</td>
<td>Invar foils with hole grid</td>
</tr>
<tr>
<td>Multi-material sphere</td>
<td>Technologica</td>
<td>Ruby</td>
<td>L20 Ø10, Ø29, Ø28</td>
<td>University of Padova, Italy</td>
<td>Glass Fibres</td>
<td>12 fibres Ø1125 L350 to 700 µm</td>
</tr>
<tr>
<td>Spheres of different diameters</td>
<td>1 Center AIMEN, Spain</td>
<td>-</td>
<td>-</td>
<td>Hole plate</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Standard shape and features</th>
<th>Aims</th>
</tr>
</thead>
</table>
| 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.](image)

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.](image)

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).

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.

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.

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Power (W)</th>
<th>Exposure time (s)</th>
<th>Filter</th>
<th>Number of projections</th>
<th>Number of frames per projection</th>
<th>Binning</th>
<th>Scan duration</th>
<th>Reconstructed voxel size (µm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>20</td>
<td>2.8</td>
<td>1 mm Sn</td>
<td>1571</td>
<td>8</td>
<td>2x2</td>
<td>12 h 21 min</td>
<td>36.0x36.0x36.0</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Insert material</th>
<th>Voltage (kV)</th>
<th>Power (W)</th>
<th>Exposure time (s)</th>
<th>Filter</th>
<th>Number of projections</th>
<th>Binning</th>
<th>Scan duration</th>
<th>Reconstructed voxel size (µm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>40</td>
<td>10</td>
<td>9</td>
<td>LE1</td>
<td>3201</td>
<td>1x1</td>
<td>9h 26min</td>
<td>19.36x19.36x19.36</td>
</tr>
<tr>
<td>SS</td>
<td>120</td>
<td>10</td>
<td>5</td>
<td>LE1</td>
<td>3201</td>
<td>1x1</td>
<td>6h 42min</td>
<td>19.36x19.36x19.36</td>
</tr>
<tr>
<td>SS zoom</td>
<td>140</td>
<td>10</td>
<td>52</td>
<td>LE1</td>
<td>3201</td>
<td>1x1</td>
<td>49h 26min</td>
<td>5.65x5.65x5.65</td>
</tr>
</tbody>
</table>
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.

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