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Foreword

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Introduction

X-ray Computed Tomography (XCT) is used for many aspects of quality control of parts in the industry, i.e. three-dimensional (3D) visualisation in volume for function testing, Non-Destructive Testing (NDT) or Non-Destructive Evaluation (NDE) for flaw analysis, but also metrology for nominal/actual comparison, tolerance analysis, and dimensional measurements.[1,2] This increased adoption can be explained by the fact that additive manufacturing (AM), producing parts with complex geometries that can contain internal features, is becoming increasingly popular in the industry. Parts conventionally manufactured without internal features, are dimensionally measured by surface methods, providing a 3D surface point cloud (discrete set of data points in space) obtained, for example, using a coordinate measuring machine (CMM). However, surface methods, for complex geometries with internal features, are no longer appropriate. Therefore, XCT, a 3D volumetric non-destructive testing method, capable of adapting to complex geometric shapes and rough surfaces, providing the visualisation of the whole volume of a test part (geometric 3D representation of the inside and outside) is required for AM to perform internal dimensional measurements.

Performing dimensional measurements on a 3D volumetric XCT data is a complex process as XCT is a complex process involving several steps:

1) specifying rigorously, with the customer, the measurands of interest in the test part in a defined coordinate system;

2) defining a dimensional measurement protocol, i.e. a measurement strategy;

3) the XCT scan of the test part to get its projections over 360° (2D images). These projections correspond to a mapping of pixels with different grey values representing the transmission of the X-ray beam by the test part;

4) the reconstruction of the 3D volumetric XCT data from the projections, using a dedicated algorithm. This 3D volumetric XCT data is composed of voxels (3D pixels) with the different grey values;

5) determining the boundary between background and materials (surface determination or segmentation). This step converts the 3D volumetric XCT data composed of voxels with different grey values to a surface model, for e.g. composed of a point cloud or a set of vertex;

6) the registration of the test part, in the used analysis software, with its computer-aided design (CAD) model to position it into the defined coordinate system (this step can be preceded by a surface exportation to process the data in another software);

7) fitting geometrical elements on the features to be measured in the test part;

8) performing the dimensional measurements of the defined measurands according to the predefined dimensional measurement protocol, i.e. dimensional measurement strategy.

All these steps (Figure 1) are influenced by several factors. These influence factors considerably complicate the dimensional measurement uncertainty evaluation and, until now, have prevented a generalised uncertainty from being provided to all dimensional measurements (i.e. to all measurands and to all XCT settings). However, there is a growing need for using XCT systems for dimensional measurements of AM series production parts and, without standards, the full acceptance of the XCT technique for metrology of AM parts cannot happen. Consequently, this document, proposes a methodology to be followed prior to performing dimensional measurements on 3D volumetric XCT data of AM series production parts, in order to validate the dimensional measurements of their measurands of interest and to provide a simplified method for assessing their dimensional measurement uncertainty.

The process to be followed prior to performing dimensional measurement on 3D volumetric XCT data of AM series production parts, in this document, is divided into two steps:

— Step 1: Qualification of an XCT system performance, in terms of image quality, with an Image Quality Indicator (IQI), and in terms of basic dimensional measurement accuracy, with a reference object and eventually Representative Quality Indicators (RQI),[3,4] with the specific part (part chosen from the AM series production parts) XCT settings under certain environmental conditions. This step leads to

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the determination of the initial image quality and its stability over time, the voxel size and the basic dimensional measurement accuracy of the XCT system;

— Step 2: Validation of the XCT system conformity, in terms of dimensional measurement accuracy, with the specific part, with the chosen XCT settings, under the specific environmental conditions. This step leads to a simplified determination of the dimensional measurement uncertainty of each measurand of the specific part. These uncertainties shall be examined in relation to the expected tolerance before to allow carrying out the dimensional measurement on the AM series production parts.

If step 1 does not comply with the set requirements, the XCT system cannot be used for step 2.

These initial qualification and validation processes, which allow dimensional measurements to be carried out on 3D volumetric XCT data of AM series production parts, are valid for a specific part geometry in a given material associated with a chosen XCT settings (magnification, and XCT acquisition and reconstruction parameters of the specific part) under specific environmental conditions for the measurands specified. The qualification and validation processes shall be reconsidered when different geometry of the part or material or XCT settings or environmental conditions or measurands are different.

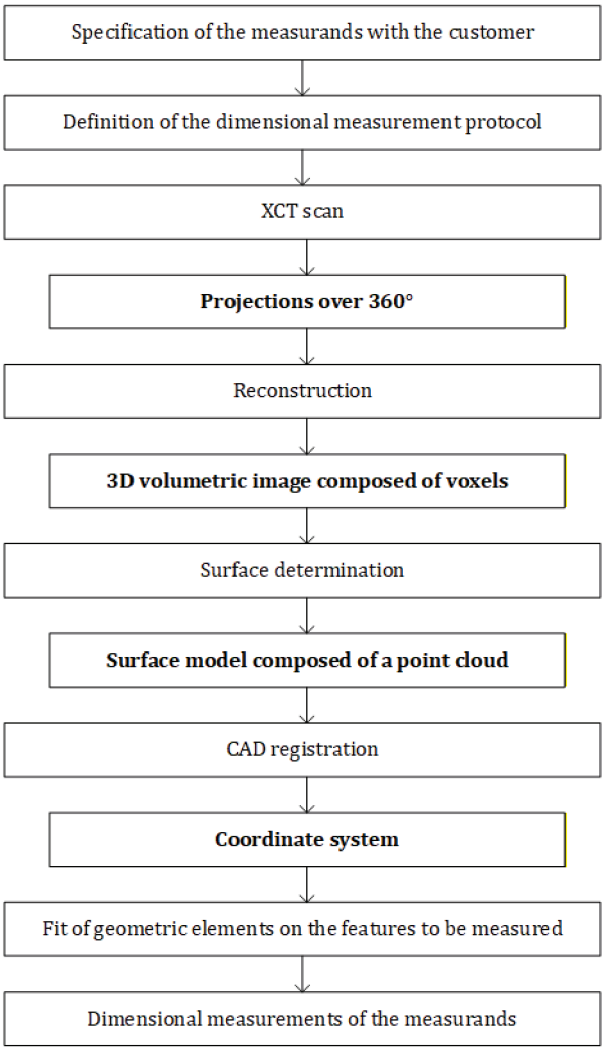


Figure 1 — Flow chart presenting the different required steps to perform dimensional measurements on an 3D XCT volumetric data

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Additive manufacturing — Non-destructive testing and evaluation — Guideline for dimensional measurements based on cone beam X-ray Computed Tomography

1 Scope

This document specifies requirements and recommendations to be followed prior to carrying out dimensional measurements on three-dimensional (3D) volumetric X-ray Computed Tomographic (XCT) data of additive manufacturing (AM) series production parts. It is applicable to cone beam XCT systems. However, these requirements and recommendations can be transposed to non-medical fan beam XCT systems, but they are limited to standard XCT trajectories (circular and helical) and standard reconstructions.

The proposed methodology in this document is restricted to the qualification and validation of an XCT system prior to proceeding to dimensional measurements on specific AM series production parts and cannot be generalised to any application.

This document provides a method to evaluate XCT dimensional measurement accuracy. However, it does not claim to provide a definitive method, given the complexity of an XCT process. For the same reason, it is addressed to qualified XCT operators with the support of metrology experts.

This document is dedicated to AM series production parts and its aim is to provide a methodology for controlling the geometric specificities associated with AM (internal shapes, lattice structures). It is applicable on parts that are fabricated by any type of AM categories of processes and material provided the X-ray penetration lengths are sufficient to scan the test part.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 15708-1, *Non-destructive testing — Radiation methods for computed tomography — Part 1: Vocabulary*

ISO 15708-2, *Non-destructive testing — Radiation methods for computed tomography — Part 2: Principles, equipment and samples*

ISO 15708-3, *Non-destructive testing — Radiation methods for computed tomography — Part 3: Operation and interpretation*

ISO 15708-4, *Non-destructive testing — Radiation methods for computed tomography — Part 4: Qualification*

ISO 5725-2, *Accuracy (trueness and precision) of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method*

ISO 5725-4, *Accuracy (trueness and precision) of measurement methods and results — Part 4: Basic methods for the determination of the trueness of a standard measurement method*

ISO 22514-7:2012, *Statistical methods in process management - Capability and performance – Part 7: Capability of measurement processes.*

ASTM E1441, *Standard Guide for Computed Tomography (CT)*

ASTM E1695, *Standard Test Method for Measurement of Computed Tomography (CT) System Performance*

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ASTM E2782-17, *Standard Guide for Measurement Systems Analysis (MSA)*

ASTM E3505–25, *Standard Practice for Direct Determination of Computed Tomography (CT) Detail Detection Sensitivity and Calculation of Numerical Detection Limit*

ASTM E1817-8, *Standard Practice for Controlling Quality of Radiological Examination by Using Representative Quality Indicators (RQIs)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/IEC Guide 99, and ISO/ASTM 52900 apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
AM specific part
part chosen from the additively manufactured (AM) series production parts

3.2
nyquist criterion in XCT
criterion stating the number of projections

Note 1 to entry: The number of projections shall be the maximum size of the part in pixel multiplied by π/2.

3.3
cognizant engineering organization
CEO
company, government agency or other authority responsible for the design, or end use, of the material or component for which non-destructive testing is required

[SOURCE: ASTM E1316-22]

4 Qualification of an XCT system performance

4.1 General principles

Before performing dimensional measurements on 3D volumetric XCT data of AM series production parts, the performance of the XCT system shall be qualified. The performance of an XCT system is defined in terms of image quality produced by the XCT system, and dimensional measurement accuracy allowed by the XCT system. The proposed qualification consists in two steps:

a) Quantification of the image quality of the XCT system by determining the Modulation Transfer Function (MTF) and Detail Detection Sensitivity (DDS), as defined in ASTM E1695 and E3505 (see also [5,6]), with the specific part XCT settings under certain environmental conditions to record its initial performance in terms of image quality and to monitor the long-time image quality stability. This step involved using an Image Quality Indicator (IQI);

b) Calibration, as defined in ISO/IEC Guide 99, of the voxel size, if not done previously, and quantification of the dimensional measurement accuracy of the XCT system with the chosen XCT settings under the specific environmental conditions to determine its basic performance in terms of dimensional measurement accuracy. This second step also consists of two steps:

    1. Calibration of the voxel size and quantification of the influence of the XCT system hardware geometry using a reference object to quantify the basic dimensional measurement accuracy of the XCT system;

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