euspen's 23rd International Conference & Exhibition, Copenhagen, DK, June 2023
www.euspen.eu

Case study of X-ray Computed Tomography performance in polymeric additive manufacturing features evaluation

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Abstract
Additive manufacturing (AM) development has increased the metrological requirements of newly designed parts due to its design freedom. X-Ray computed tomography (XCT) has become a suitable measurement technique for these parts, as a non-destructive evaluation technology able to characterise both internal and external features. This paper presents an evaluation of XCT performance in the measurement of polymeric AM features, and its capability to differentiate polymers with slight density variations. Precision spheres of various polymers have been used as high quality elements to evaluate, and CMM reference measurements have been taken for part calibration. Results show good threshold differentiation for a density variation equal or higher than 0.16 g/cm^3, and indicate a contribution of surface quality in deviation of distance measurements.

Keywords: X-Ray computed tomography, Additive manufacturing, Multi material.

1. Introduction

The development of additive manufacturing (AM) technologies has allowed to create more complex designs [1], which are impossible to produce by other traditional techniques, with an important material-saving in comparison. In addition, the improved characteristics of the parts and the wide range of available materials give those technologies the versatility needed for end-use products.

As a consequence, new metrological techniques have become necessary to be able to characterise those sophisticated features. Industrial X-Ray computed tomography (XCT), based on a 3D reconstruction of a series of 2D X-Ray images around the measured part, has become an appropriate solution for it. This technology is able to evaluate not only the surface, but also the inside of an object, being capable of characterising internal elements [2,3].

Material plays an important role in XCT settings. X-Rays penetration capacity lowers as the density of the material increases, so the configuration changes depending on material, part thickness and shape; moreover, multi-material assemblies, which are realistic scenarios for industrial parts with multi material features, need a more precise adjustment for a proper characterisation [4,5]. Recent research in this field is more focused in high-performance metal alloys [6] due to its intrinsic properties; however, polymers are widely used in most fields of production, specifically in AM due to the lower production cost.

In this paper, an evaluation of various polymeric features by means of XCT has been carried out. The target is to evaluate the capabilities of XCT when measuring polymers with slight differences in density, and the effect of manufacturing surface quality of the part in the measurement process. An ad hoc assembly made of various polymers has been designed, in which a base with AM spheres and hollow cylinders, and precision polymeric spheres are included for metrological evaluation and comparison. Reference measurements were taken before and after XCT evaluation to calibrate the part and to ensure no significant deformation occurred over time.

2. Design and materials

Precision spheres with nominal value of Ø12 mm have been selected to be compared with AM spheres and cylinders, with a tolerance of 25 µm in diameter and 12 µm in form error. Distances between centers of spheres are solid dimensions, because they are not as dependant of determined surface as plane-to-plane measurements. Also, diameters of spheres offer good stability.

Four materials have been selected for the precision spheres: PTFE, POM, PP and PA6. A base is designed and manufactured by Polyjet technology, printed in photopolymer Rigur™ RGD450, where four spheres of each material were distributed in four groups along the base. Five AM printed spheres (Ø12 mm) and eight hollow cylinders (Ø8 mm) are included in the base. CAD model of the assembly with general dimensions and the distribution of the elements is shown in Figure 1.

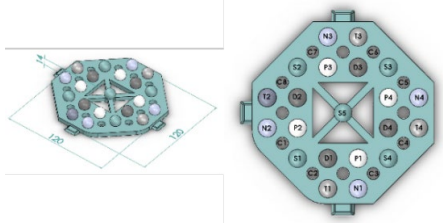

Figure 1. CAD model and general dimensions (left), distribution of elements in the base (right).

Each group has one sphere of each material. Nomenclature: D – POM, P – PP, T – PTFE (Teflon), N – PA6 (Nylon), S – AM printed spheres and C – hollow cylinders.

3. Methodology

Three XCT measurements have been taken using a Zeiss Metrotom 1500/225 kV device. Settings are listed in Table 1.

Table 1. XCT Settings.

XCT Settings	Value
Voltage [kV]	120
Current [µA]	837
Phisical filter	Al 1mm
Nº of projections	3000
Exposure time [ms]	500
Voxel size [µm]	58

As deformations may occur, reference measurements were taken with a coordinate measuring machine (CMM) Zeiss PMC-876 CNC before and after XCT characterisation. CMM evaluation before and after XCT is critical for artefact calibration, for XCT deviation comparison and for stability check along time.

Geometries evaluated are features' diameters and form error, and distances between similar elements (same-material spheres, cylinders). AM spheres S1, S2 and S4 were used as references for alignment. Software Calypso has been used for CMM reference measurements, and VG Studio Max 3.4.2 for XCT post process. Initial surface determination (SD) in Advanced mode (search distance of 4 voxels) and second ROI local SD of each element have been performed.

4. Results

4.1. Material differentiation

In the first qualitative inspection of the results, histogram of gray values (see Figure 2) shows that 4 different peaks can be distinguished apart from the background/air peak (displayed in the left).

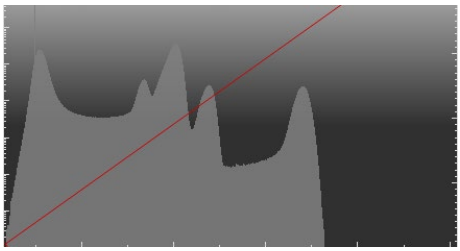

Figure 2. XCT histogram of gray values.

Through an Advanced - Multi Material surface determination, each peak has been separated into an independent volume. In Table 2, density of each material and its corresponding approximate grey value (according to its peak) is shown.

As XCT data is acquired in 16 bits, complete spectrum of grey values goes from 0 (white) to 65535 (black). Theoretically, denser materials should have higher gray values.

Table 2. Material density and corresponding XCT grey value.

Material	Density [g/cm^3]	Grey value
PP	0.87	8300
PA6	1.11	10100
Rigur™ RGD450	1.21	10100
POM	1.37	11900
PTFE	2.16	17000

Results show a correlation between density and grey value, and a differentiation between almost all materials. Only it is not possible to distinguish Rigur™ RGD450 and PA6 due to its very similar density (0.1 g/cm^3 difference). However, a differentiation between Rigur™ RGD450 and POM is possible, with a slightly higher density difference (0.16 g/cm^3).

4.2. Dimensional results

A summary of XCT deviations from CMM measurements is presented in this section. Mean values of each type of geometry have been considered. As distance nominal values are unequal for all features, µm/mm coefficient has been used for comparison. Results are displayed in Table 3.

Table 3. XCT deviations from reference CMM measurements.

Geometry	Diameter [µm]	Form error [µm]	Distance [µm/mm]
AM spheres	-30.9	45.3	0.39
AM cylinders	43.5	29.6	0.41
Prec. spheres	4.8	3.9	0.28

Negative values of diameter deviation on AM spheres are related to the layer-by-layer AM technology: only surface peaks are reachable by CMM while XCT device is able to characterise the complete topography. Same effect in the opposite direction occurs to AM hollow cylinders. AM diameter and error form deviations are 700%-900% higher than precision spheres deviations, while values of distances deviations are around 30% higher for AM features. Precision spheres' distances are strongly influenced by the AM base where they are placed; however, deviations remain lower. Further studies are necessary to evaluate each contribution in deviations.

5. Conclusions, future work and acknowledgements

A polymeric multi-material XCT evaluation, focused in AM comparison to precision features, is presented in this paper. Research have shown that differentiation between polymers with similar density is possible, with good threshold results for variations of 0.16 g/cm^3 or higher. For multi material part evaluation, this could be interesting in order to ensure proper polymer differentiation in presence of other types of materials. AM features shows higher deviations from CMM measurements in terms of diameter and form error as expected. Distances, strongly influenced by AM base, are still higher for AM features, which indicates a contribution of AM surface in distance errors.

Future work should focus on a deeper study of the contribution of each parameter to distance errors, and the feasibility of this AM features used for reference parts.

This work was supported by projects RTI2018-097191-B-I00 and PID2021-127134O-B-I00 funded by MCIN/AEI/ 10.13039/501100011033 and by ERDF A way of making Europe; and by grant PRE2019-089465 funded by MCIN/AEI/ 10.13039/501100011033 and by ESF Investing in your future.

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