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Estimation of the accuracy of measurement of internal defects in X-ray Computed Tomography

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Abstract

Additive Manufacturing technologies found many applications in the last decade in many industries. AM parts show good mechanical properties, but the presence of porosity is still limiting the adoption of these technologies on a wider scale. X-ray computed tomography (XCT) has become a successful measurement tool to characterize AM parts, especially for detecting defects. In this work, a test object was used to simulate internal porosity and test the accuracy of the XCT measurement. Repeatability and reproducibility of the XCT system were investigated as well as the influence of the internal defects position and size on the measurement error.

Keywords: X-ray computed tomography; Repeatability; Reproducibility

1. Introduction

X-ray computed tomography (XCT) is a Non-Destructive Technique used for the mechanical characterization of objects. X-rays are used to create cross-sectional images of the object at different rotation angles, these images are then reconstructed using specific algorithms [1]. XCT output is a 3-dimensional information about the scanned object. Due to the advantages of X-Ray Computed Tomography, e.g. the Non-Destructive Testing of both internal and external features and the relative rapidity of the process, this technology has been used in different fields such as additive manufacturing, forging and so on. In particular, the use of XCT for the characterization of additive manufacturing parts has become more and more common [2], [3]. Additive Manufacturing is now an established set of technologies that offer the opportunity to produce parts directly from 3D CAD models. Porosity and internal defects are some of the main disadvantages of AM parts which are slowing down a more widespread diffusion of the technology. Pores usually form during the printing phase, and their on-line detection is difficult, and it is also difficult to understand their influence on the final part properties [4]. For this reason, XCT has been used in combination with AM processes aiming at studying the porosity structure (size, shape, and position) to estimate AM parts mechanical properties, such as fatigue [3],[5].

The absence of a metrological procedure for the validation of the accuracy of the XCT porosity measurement has been an interesting topic of research. Past examples of studies on the accuracy of XCT using a reference object can be found in [6] and [7]. More recently, two papers investigated this problem with a prospective on Additive manufacturing. Hermanek and Carmignato [8] designed an object for the accuracy investigation in XCT. The authors developed an object to simulate internal porosities consisting in 4 cylindrical aluminium samples of different heights, with micro-milled holes on the bottom plane surface. The cylinders were then inserted in an aluminium case with four cavities to simulate closed porosities. This concept was improved by the same authors in [9] by removing some of the critical issues in their former solution. In the new design, one bolt for each cylinder

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was added to the reference sample to provide a pressing force and eliminating the slippage during the rotation of the table in the tomographic process. A non-symmetric pattern of 16 hemispherical holes was micromilled and then measured using a more precise instrument than the XCT. The objective is to have a reference measurement of the geometrical dimensions of the features, such as diameters, depths, and volumes to use as a comparison with XCT. There are still some topics that need further attention and that are addressed in this preliminary work. Among them, there is the influence of the position of the pores on the quality of the measurement. This preliminary study investigates the quality of the XCT measurement by focusing on the following aspects: the influence of the vertical position of the calibrated features and the influence of the position of the features on the reference object. To carry out this experiment, a new reference object was designed. The paper is organized as follows: Section 2 describes the reference object and its properties, Section 3 defines the experimental campaign, in Section 4 we report the results of the analysis and in Section 5 we discuss the results and future developments.

2. Reference object design and measurement procedure

To assess the quality of the XCT measurement, the acquired data should be compared with the same measurements obtained with a more precise system. The metrological instrument chosen for the comparison is a high-resolution microscope which allows the 3D reconstruction of small features. The selected system is Alicona Infinite Focus, a microscope using focal variation to obtain high resolution 3D images of surfaces. The design of the sample was carried out to allow both instruments to measure the features of interest. The second constraint faced in the design was the size of the features to be measured. As the reference application of our analysis is AM, the dimensions we would like to analyze are smaller than 350 µm to mimic in the best way possible the porosity found in AM parts.

2.1. Reference object design

The reference object is made up of 4 small disks of aluminum. On the top surface of each disk, a series of milled features were machined to obtain the smallest diameter and depth possible. The milled cavities can be directly measured with the microscope. To create the internal features during the XCT measurement, the disks were positioned one above the other to create a cylindrical sample. The upper surface of the disk (the one with the milled cavities) is in contact with the lower surface of the adjacent disk, which is completely flat. The disks were produced from an extruded aluminum bar. The dimensions of the disks are height 1.3 mm, diameter 6 mm. An example of disk with milled features on the surface is showed in Fig. 1.To obtain the highest parallelism possible between the surfaces of the disks and between different disks, together with a better finished surface, a further operation of micromilling was performed using KERN Evo machine, an ultra-high precision CNC mill. Once that the disks had been polished, to maintain the ultra-high precision of the machine, the operations of micromilling were performed in sequence. A pattern of 36 marks was designed by generating random combinations of radial (ρ) and angular positions (θ), visible in Fig. 1 a). The random distribution of this pattern allows for the study of the influence of ρ and θ on the performances of the XCT measurements. A total number of 6 disks were produced.

Two groups of 3 disks were produced using two different tools with the same shape (conical). The first group (SET 1) has features with a mean diameter of 326 µm and a mean height of 46 µm, while in the second group (SET 2) the milled cavities have a mean diameter of 120 µm and a mean height of 98 µm. A summary of the features size is reported in Table 1. The fact that the cavities do not have all the same size is not a problem, as their dimensions were directly measured using the microscope. In conclusion, the reference object is composed by multiple disks overlaid on top of each other. On the upper surface of the disks, milled cavities were produced to simulate a cylindrical component with internal porosity. To avoid the relative movement of the disks during the scan, two identical cases (upper and lower) and some spacers were designed. A case with an external diameter equal to 30mm, an internal one of 6.1 mm and a height equal to 10 mm was designed and produced using 3D plastic printers

Table 1. Summarized statistics of the size of the milled features on SET 1 and SET 2

	Diameter (µm)		Height (µm)	
	Min	Max	Min	Max
	310	354	43	58
SET 1	293	341	41	54
	298	335	41	51
	100	120	97	110
SET 2	109	121	92	102
	108	123	93	108

We used Polylactic acid, commercially known as PLA. The internal diameter of the case is larger enough to allow the placement of the disks but also to force them in their position. To compact the aluminium disks, PLA disks were printed and placed above the aluminum disks during the scan. The overall schematization of the reference reference object is showed in Fig. 2.

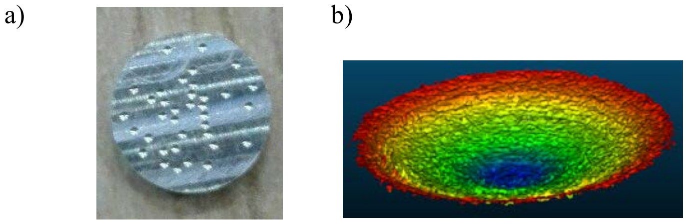

Fig. 1. a) Picture of one disk with the milled features on the upper surface b) example of reconstruction of one feature

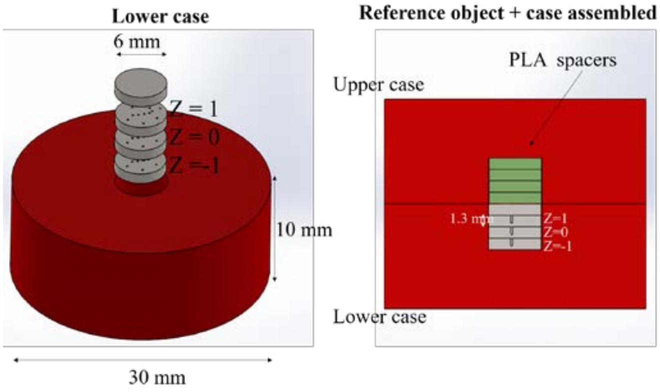

Fig. 2 Schematization of the reference object

2.2. XCT and microscope measurement

The XCT system used is NSI x25 by North Star Imaging. All the scans were performed with the same parameters, Voltage (125 kV), Power (5.5 W), number of projections per scan (1440) and number of averaged frames (3). Images were reconstructed using NSI software, edX-rf. The voxel size used for all the scan is 5.5 µm, the highest magnification that it was possible to obtain. Using the Otsu method [10], a .STL object was created from the slices. Then, using CloudCompare software, the individual cavities were isolated, as the one in Fig. 1 b), and analyzed with a self-developed Matlab code. Alicona Infinite Focus microscope was used as reference for the XCT measurement. The output of the microscope acquisition is a .STL file of the overall surface of the disks, then using CloudCompare software the individual features were separated. The same Matlab code used for XCT was implemented on the microscope .STL files.

3. Experimental campaign

Two different analysis were carried out: repeatability and reproducibility. In the repeatability study, once the disks were piled up and inserted in the case, the XCT measurements were performed twice in a row (using SET 1). In the reproducibility case, after the first measurement, the case and the disks were disassembled, and the machine shut down. Later, the measurement was repeated a second time (using SET 2). The objective is to study which factors might influence the quality of the measurement performed with XCT. In this paper, we focused on three space-related factors. The first two are the position of the milled cavity on the surface of the disk, i.e. their radial and angular position, respectively ρ and θ. The third factor is the vertical position, Z. As the disks are piled up, there is a lower disk (Z=-1), a middle disk (Z=0) and a higher disk (Z=1). Looking at Fig. 2, disk 1 is in position Z=-1, disk 2 is in position Z=0, and disk 3 is in position Z=1; disk 4 is used to close the cavities on the top of disk 3. It is known that cone beam [1] artifacts influence the quality of the XCT measurement, by considering the vertical position we can analyze and determine whether the cone beam artifact has a statistical influence on the XCT measurement. For each feature or milled cavity, 4 quantities were measured: Diameter, D (µm), Height, H (µm), Surface Area, A (mm2) and Volume, V (mm3). The statistical analysis is carried out in terms of relative error, according to the following formula:

$$\text{Error}_X = \frac{\left|X_{XCT}\left(\rho,\vartheta,Z\right)-X_{\text{Ref}}\right|}{X_{\text{Ref}}} \tag{1}$$

Where X is one of the measurands and X_{Ref} is the value of the measurement performed with the microscope. For each test (repeatability and reproducibility) statistical analysis is carried out to determine the significant factors affecting the error in the measurements.

4. Results and discussion

4.1. Repeatability study

In the repeatability study, the reference object and the case were assembled once and then scanned twice consecutively. In Fig. 3 the row from repetition 1 is plotted against repetition 2. If there is no difference between the repetitions, the data should lie on a straight line. The fitted line shows that the measurements can be described by a straight line with an angular coefficient close to 1. We conclude that the measurements related to corresponding cavities of the two repetitions are very close to each other. Since the two repetitions give redundant information, the corresponding measurements are averaged and the relative errors between the two repetitions (according to eq (1)) are used as response variables in the regression analysis. In Fig. 4 the main effect plot of diameter and height are showed. We see that the radial position ρ appears to have a strong influence, especially for the height. While the influence of the radial position θ is less clear. The vertical position Z appears to be the most significant factor with a quadratic effect for both D and H. However, for the diameter, the lowest deviation from the nominal dimension was for the middle disk (Z=0), while for the height, the minimum deviation is obtained at Z=-1 and Z=1. Main effect plots of Surface area and volume are not shown because their patterns are similar to the one in Fig 4 a). For each response, four different regression analyses were carried out and the Box-Cox transformation (using optimal λ suggested by Minitab software) was applied to validate the assumptions on the standardized residuals. A summary of the results is shown in Table 2. For each measurand, a regression equation was fitted with an intercept, ρ, θ Z and Z^2. The p-values of the factors are reported along with the standard error of the regression (s) and the adj-R^2 coefficient. The factors ρ, Z and Z^2 are highly significant for all four responses (diameter, height, surface area and volume), indicating a clear pattern bonding the different dimensions measured. The angular position is significant only for the height. The standard error indicates how much variability is described by the regression equation; generally, the lowest standard error, the better. Surface area and volume are the product of linear quantities, so they are more difficult to estimate, and the error is higher. A further result is the sign of the difference between the XCT measurement and the reference one: height was overestimated, while the other measurands were underestimated. This result could be due to the shape of the cavities which does not allow a good definition of the lower end and to the thresholding method used. Further investigation on this result is needed.

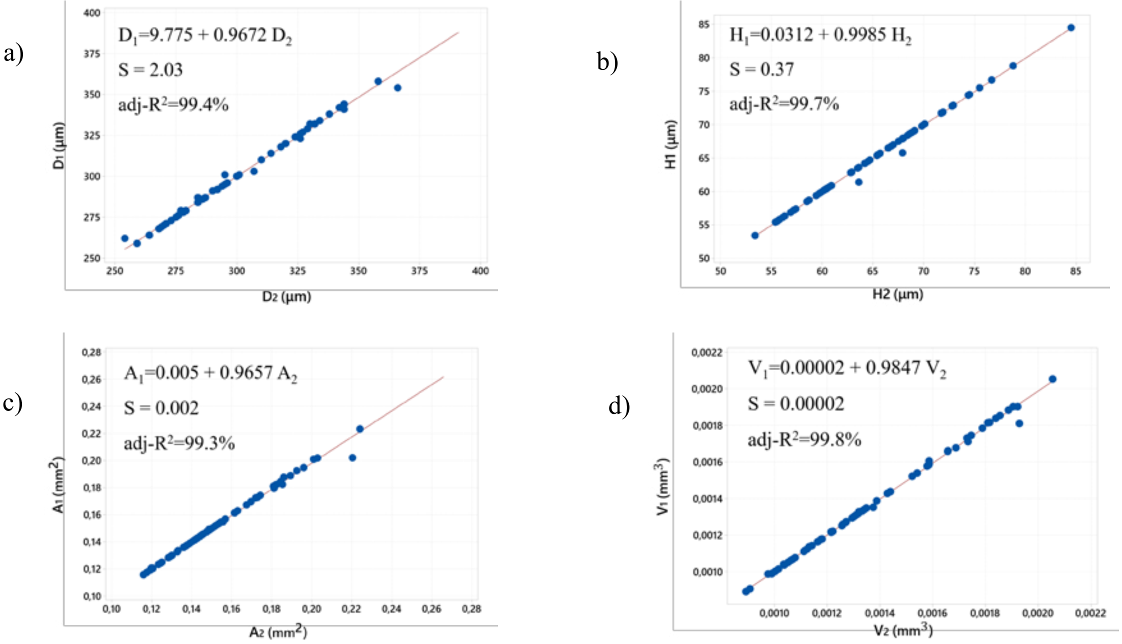

Fig 3. Fitted line plot between data from repetition 1 vs repetition 2. a) Diameter, b) Height, c) surface area and d) Volume

4.2. Reproducibility test

The reproducibility test was designed to quantify the error done when between two consecutive measurements, the disk, and the case are completely disassembled, and the machine shut down. This information helps to understand if and how a replicate of the measurement can influence the result and, consequently, how to predict it. The fitted line plots for all the measurands are shown in Fig 5. Data from replicate 1 are plotted against the data from replicate 2. The results are establishing that there is no clear pattern in all four measures, which means that the replicates are not similar one with the other. The adj-R^2 are much lower than the repeatability study, and the variability is much larger. As a result, "replicate" is added as a factor in the regression models. The results indicate that the assembling and the set-up of the machine have an impact on the quality of the measurement. From the Main effect in Fig 6, we see that the radial position is still influential in terms of deviation from the nominal data for diameter and height. The main effect plots of surface area and volume are not reported as they show similar behavior as for the diameter. The angular position, as before, appears to have a low influence. Z and Z^2 again are influential in terms of the quality of the measurement.

Table 2. p-values of the regression equation for the four measurands, standard error s, parameter λ and the adj-R2 for the repeatability test.

	ρ	θ	Z	Z2	s	λ	Adj-R^2
Error D	0.000	0.957	0.000	0.000	0.02	1.37	85.9%
Error H	0.000	0.005	0.000	0.000	0.09	0.5	69.5%
Error A	0.000	0.838	0.000	0.000	0.05	1.41	83.8%
Error V	0.180	0.816	0.000	0.000	0.07	1.39	80.7%

As in the previous section, the regression results are reported in terms of p-values of the factors (ρ, θ Z and Z^2), standard deviation of the regression equations s, the parameter λ of the Box-Cox transformation, and the adj-R^2. The summarized regression results are in Table 3. The radial position has again a strong influence on all the measurements. The vertical position Z appears to have a smaller influence on the repeatability test. However, in the case of diameter, surface area and volume the quality of the regression were highly reduced due to the larger variability of the data (see Fig. 5), as we can see from the adj-R^2 values and the increased s. The comparison of the regressions (by anti-transforming s using λ) shows that diameter and height have similar standard errors (0.003 and 0.005, respectively). On the contrary, for surface area and volume the results are much worse (0.011 and 0.012, respectively).

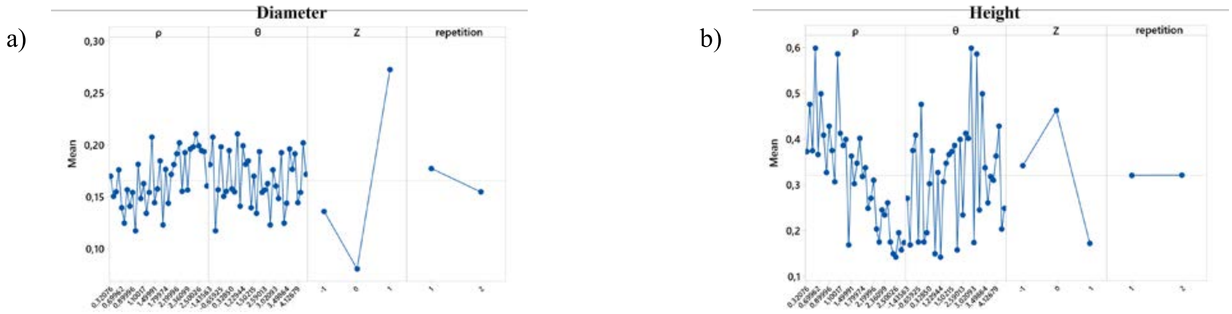

Fig 4. Main effect plot of a) diameter b) height in the repeatability test

5. Conclusions

In this preliminary study, the influence of the position of the pores on the quality of the measurement in an industrial XCT system was carried out. A new reference object was designed for the experimentation. The goal was to allow the direct measurement of the cavities, which represents the porosity of a real manufactured part, with a high precision measurement system and, on the other side, allow them to be "internal" during an XCT scan. The influence of the position of the cavities on the disk and the vertical position of the disk Z were analyzed using statistical methods. The results showed that the radial position ρ has a strong influence on the quality of the measurement, as well as the vertical position. The vertical position often has a quadratic effect, meaning that the measurement deviation in the center disk is different from the one in the top and bottom disk.

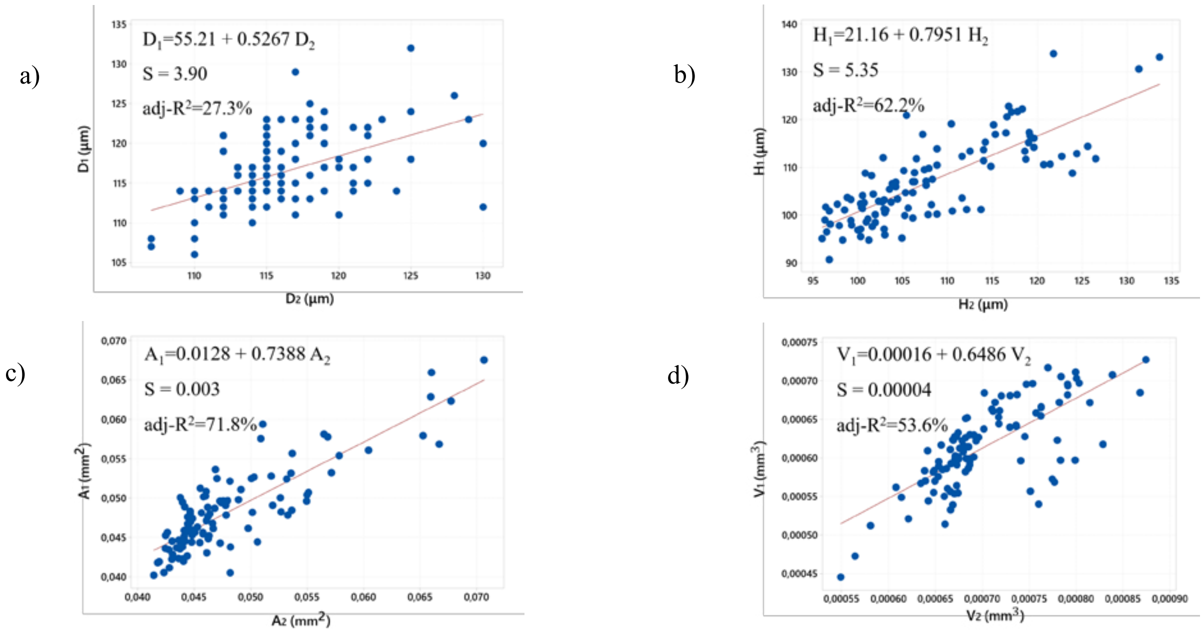

Fig 5. Fitted line plot between data for replicate 1 vs replicate test 2. a) Diameter D, b) Height, c) Surface Area and d) Volume.

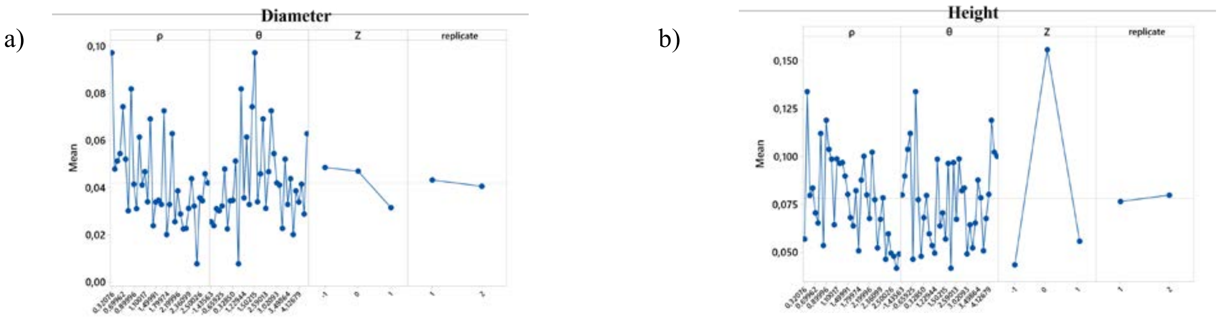

Fig 6. Main effect plot of a) diameter b) height in the reproducibility test

The repeatability test showed the high precision of the XCT measurement. In the reproducibility test the precision was reduced. Future works will be focused on studying the influence of the size of the milled features and the material of the reference object on the accuracy of the XCT measurement.

Table 3. p-values of the regression equation for the four measurands, the regression standard error s, parameter λ and the adj-R^2 for the reproducibility test.

	ρ	θ	Z	Z2	s	λ	adj-R^2
Error D	0.000	0.028	0.000	0.006	0.1	0.40	18.4%
ErrorH	0.000	0.367	0.010	0.000	0.07	0.5	60.2%
Error A	0.000	0.969	0.182	0.000	0.1	0.5	22.6%
Error V	0.003	0.009	0.959	0.000	0.11	0.5	19.6%

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