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Investigation of X-ray computed tomography for dimensional measurement

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Abstract
Driven by the need for quality control of complex three-dimensional engineering components such as those by additive manufacturing (AM), X-ray computed tomography (XCT) has been increasingly adopted for industrial inspection in recent years. However, XCT for dimensional measurement is complex and subjected to a number of factors for influencing the measurement results. In order to have a measurement traceability linked to the basic SI unit, related measurement uncertainty needs to be provided for the measured dimensions. This paper presents physical and metrological characterization and measurements conducted for an XCT system. Those key influencing factors including sample's material & shape difference, X-ray tube's power/voltage & current, beam hardening, geometrical magnification and surface determination and etc., which contribute to the uncertainty, are quantified respectively. Based on those resulting dimensional measurement results subjected to the key influencing factors, it is found that the maximum dimensional differences between XCT and traceable coordinate measuring machine (CMM) or digital micrometer (DM) measurements generally lie within 10 µm for all samples measured dimensions up to 20 mm. The proposed experimental uncertainty evaluation based on the Guide to the Expression of Uncertainty in Measurement (GUM) are worked out to estimate the dimensional measurement uncertainty by XCT. It demonstrated that the accuracy of dimensional measurements using XCT could be in the order of micrometres for the assessment of external and internal dimensional structure.

X-ray computed tomography, Measurement uncertainty, Traceability, Coordinate measuring machine (CMM), Digital Micrometer

1. Introduction

X-ray computed tomography (XCT) has been becoming an established technique for non-destructive analysis in various fields of application. As an advanced measurement technology for dimensional quality control, XCT is increasingly employed by industry due to its capabilities to provide geometric information of inner and hidden structures of complex or assembled parts. Nowadays, additive manufacturing (AM) as an emerging technology has widely been adopted to produce/repair a part through a layer-by-layer process during AM [1]. Compared to those conventional subtractive manufacturing, AM's adding layer by layer process has its unique advantage to build complex components based on digitized CAD model for AM machine. Meanwhile, AM gives a challenge for those complex components to be properly measured in quality control since those contact and non-contact dimensional measuring tools [2-4] have some limitations, such as no enough access to internal structure, measurement distortion at a higher surface slope, deformation due to a measuring force and etc. The utilization of XCT for dimensional measurements of micro and macro parts [5-6] is capable of overcoming the challenge resulting from AM. This is because XCT allows the acquisition of AM part's internal and external geometries at a high dense sampling points to detect and measure those hidden structure based on X-ray's penetration through workpieces' materials and subsequent CT images can carry dimensional information of those internal structures. However, XCT has still not been widely accepted as an accurate measurement tool in manufacturing industry's dimensional control due to its high operator dependency and lack of measurement traceability. Obviously, measurement results without claimed measurement uncertainty are also incomplete for metrological applications associated to product quality control.

In this paper, key influencing factors in determination of measurement uncertainty of GE Nanotom XCT system have been experimentally studied by the use of designed samples with different materials: Stainless steel (SS), Titanium (Ti) and Inconel (IN) and different shapes: through-hole & solid cylinders, through-hole & solid square blocks. Related dimensions are covering from 0.5 mm to 20 mm. Corresponding dimensional calibration is conducted by coordinate measuring machine (CMM; accuracy: better than 1 µm) and Digital Micrometer (DM; accuracy: better than 2 µm) as reference equipment. The measurement errors resulted by those influencing factors are analyzed by comparing measurement results of designed samples measured by XCT to traceable standard equipment CMM and DM.

2. Method

2.1. Sample design and reference dimensional determination

As shown in Figure 1, those designed samples' dimensions are covering from 0.5 mm to 20 mm by considering XCT's penetration capability.

In order to evaluate XCT's dimensional measurement accuracy, as shown in Figure 2, 12 samples by subtractive fabrications are in the shapes of through-hole/solid cylinders and through-hole/solid square blocks. The materials used in the fabrication

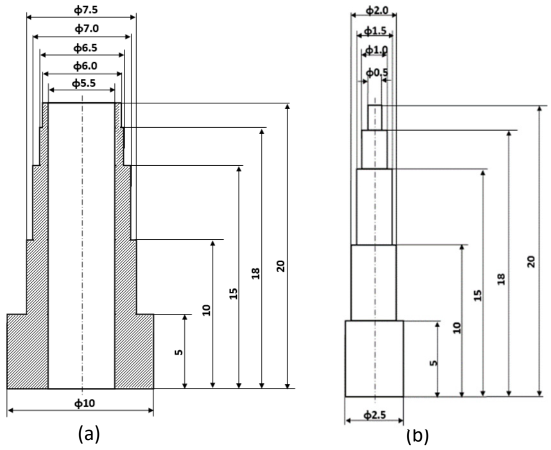


Figure 1. Mechanical drawing for the design of (a) through-hole and (b) solid samples with related dimensions measured by standard reference equipment and XCT for comparison and verification of the dimensional measurement accuracy.

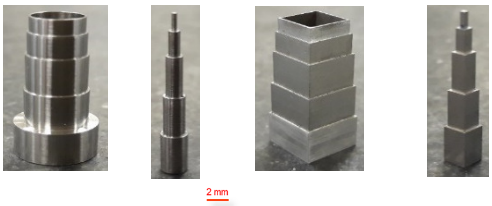


Figure 2. Photos to show the fabricated samples in different shapes made from stainless steel (SS), titanium (Ti) and Inconel (IN).

are stainless steel (SS), titanium (Ti) and Inconel (IN) respectively.

Corresponding dimension calibration has been conducted by CMM (accuracy: better than 1 µm)/Digital Micrometer (accuracy: 2 µm) as Reference equipment. As an example, Figure 3 shows the measurement conducted by a coordinate measuring machine (CMM) through a contact ruby ball stylus (0.5 mm).

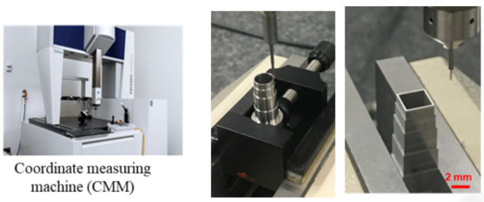


Figure 3. Setup to demonstrate samples' dimension measured by a CMM.

2.2. X-ray computed tomography (XCT)

The XCT working principle is shown in Figure 4. A number of 2D projection shadow images are recorded accordingly in line with the sample's rotation on the platform. However, XCT shadow image different from the visible light shadow [7] has its X-ray to penetrate the sample materials for obtaining internal/hidden dimensional structures. After a 3D image reconstruction, 3D volumetric dimensional information can be obtained by a post-data process in Volume Graphic program (Volume Graphic 3.0) [8].

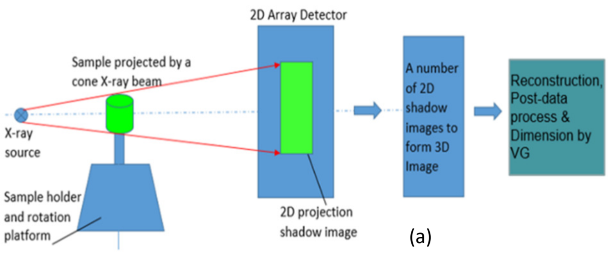


Figure 4. Schematic XCT setup to show the measurement flow.

Figure 5 shows a setup of an XCT machine (Nanotom from GE) inside view, in which a stainless steel through-hole cylinder sample is scanned by XCT. In the XCT system, the X-ray source (Maximum voltage 180 kV, setting at 150 kV and 160 µA) attached with a filter (0.5 mm Cu) is set to ensure the X-ray to penetrate the sample properly. A shadow image of the sample with a minimized beam hardening effect is projected onto the detector. An example of XCT 2D projected image is shown in Figure 5(b). After collection of 2500 projections/frames of 2D XCT images and reconstruction of XCT images with a voxel size of about 10 µm, related dimensions can be determined.

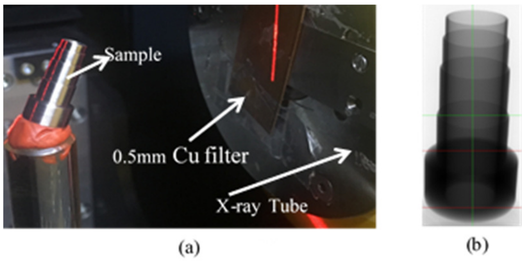


Figure 5. (a) An XCT setup and (b) A 2D shadow image of the sample recorded by detector.

3. Results and discussion

3.1. Dimensional measurement of samples with different shapes and materials

As an example shown in Figure 6, a cylinder through-hole sample (Stainless Steel material) was measured by XCT. It is seen

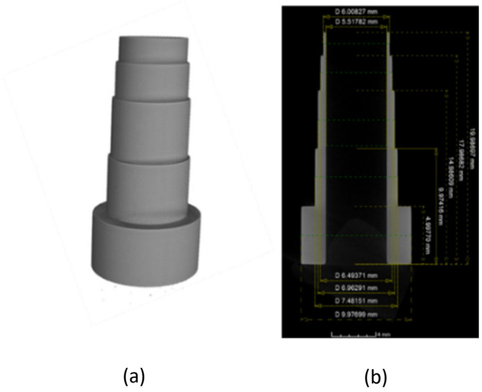


Figure 6. (a) 3D XCT image obtained through the measurement scanning of a cylinder through-hole sample (Ti material) and (b) 2D plot to show those measured dimensions.

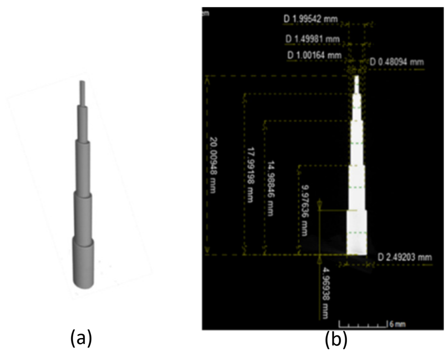


Figure 7. (a) 3D XCT image obtained through the measurement scanning of a cylinder solid sample (Stainless steel) and (b) 2D plot to show those measured dimensions.

that corresponding 3D and 2D XCT images are clearly obtained and the 11 dimensions referred to those in Figure 1(a) have been determined in Figure 6(b). Similarly, for a cylinder solid sample (Stainless Steel material), all dimensions to be measured can be referred to those in Figure 1(b). Figure 7 shows 3D and 2D XCT images obtained using the same XCT scan setting as in the measurement by XCT.

After compared with corresponding reference values, the measured deviations away from reference value of samples in 3 different materials are plotted in Figure 8 as for the cylinder through-hole samples. It is found that the maximum

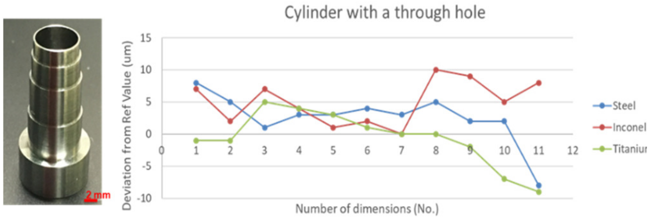


Figure 8. Summary of sample (through-hole cylinder) of dimensional measurement deviated from reference values.

(b)

variation of the dimensional deviation for the samples in different materials is within ± 10 µm for the dimensions from 5.5 mm up to 20 mm.

Figure 9 shows XCT measurement results of a solid cylinder compared to reference values. It is noted that the maximum variation of dimensional

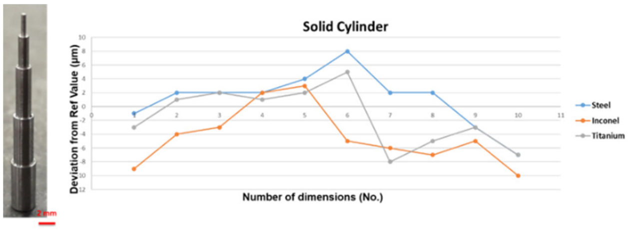


Figure 9. Summary of sample (solid cylinder) of dimensional measurement deviated from reference values.

deviations for the samples in different materials is from -10 µm to +8 µm for dimensions from 0.5 mm to 20 mm. Therefore, the measured dimension deviation from reference values is also within ± 10 µm.

Similarly for samples' shape through-hole/solid square blocks, it is found the maximum dimension deviation is also within ± 10 µm for all 3 different materials. Considering a full rectangular distribution, corresponding standard uncertainty is 10⁄√12=2.9 µm.

3.2. Voltage and Current effect to dimension measurement

In order to evaluate how XCT power (voltage & current) setting introduce dimensional errors, it is intentionally adjusting the powers as 21W (150 kV & 140 µA), 24 W (150 kV & 160 µA and 25.6W (160 kV & 160 µA) and conduct the same scanning to stainless steel through-hole cylinder sample. The measurement results are summarized in Figure 10. It is found that the change

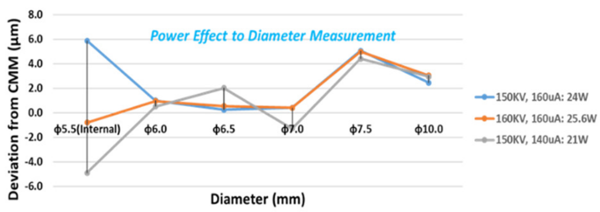
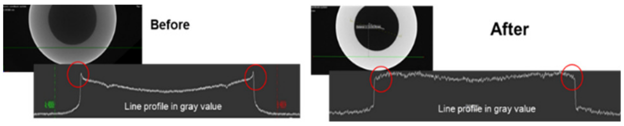


Figure 10. Summary for sample (stainless steel solid cylinder) of dimensional measurement deviated from reference values.

of XCT power could result in a variation below 2 µm for external diameter. But for internal hole diameter (ϕ5.5 mm), the variation can be close to ± 6 µm. This could be mainly because there is more X-ray scattering in the internal structure and this scattering gives more errors in surface determination/edge identification. Considering 10% power change and a rectangular distribution, corresponding standard uncertainty is 6x10%0.6⁄√3=0.35 µm.

3.3. Beam hardening effect to dimensional measurement

Since the sample is a uniform material, it is supposed to have a uniform gray distribution in XCT image. However, the influence of beam hardening on dimensional measurements is identified to be a non-uniform gray value image. As shown in Figure 11, a polychromatic X-ray results in a jumping edge at the sample boundary between the air and sample material. In this study, an



(a) (b)

Figure 11. Gray value distribution of an Inconel through-hole cylinder sample. (a) Sudden jump at the sample edge before a beam harden correction and (b) a flatten line profile distribution and the edge effect is clearly.

XCT image (Inconel through-hole cylinder) demonstrated that there is an obvious sudden jump along the sample's edge before and after beam hardening correction. It is found that this results in a maximum diameter measured difference of about 5 µm. Considering a rectangular distribution, corresponding standard uncertainty is 5⁄√3=2.9 µm.

3.4. Surface determination effect

The surface determination accuracy directly influences the sample edge location and critical dimension from one edge to

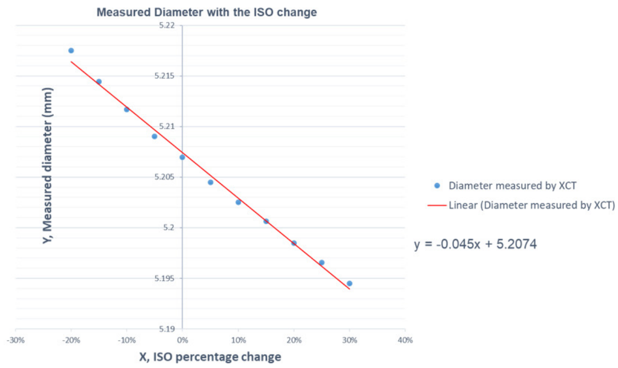


Figure 12. Relation of XCT measured diameter and the change of ISO value in surface determination.

another. To quantify the surface determination accuracy, a standard steel cylinder sample with a certified diameter of 5.1960 mm is scanned and measured in XCT by setting different Isolation value (ISO) for locating the sample's surface. By intentionally starting at ISO 50 as in VG program and changing ISO up and down, corresponding diameter can be measured respectively. Figure 12 shows the study results about the relation of ISO value change in percentage versus the measured diameter. Based on the fitted equation and considering 2% of ISO change (possibly due to X-ray intensity variation, defect, scattering etc.), it can estimate that it results in 0.9 µm diameter measurement error/deviation. Considering a rectangular distribution, corresponding standard uncertainty is 0.9⁄√3=0.52 µm.

3.5. Magnification change effect

Due to non-linearity of XCT system, the magnification also introduce errors even for the same sample but locating at various positions with respect to the geometrical distances of sample to X-ray source and X-ray source to detector in XCT system. For a given distance from X-ray source to the detector, the closer the sample to X-ray source, the higher magnification/smaller voxel size for supporting a better dimensional measurement resolution.

The standard steel cylinder with a certified diameter of 5.1960 mm is also used in the study. A summary of the measured diameter deviated from reference value is shown in Table 1. At a set magnification 10×, there is an error of 2.3 µm. It is noted that the error/deviation of the measured diameter is in the order of 0.1 µm after the magnification is over 20x/voxel size: 5 µm. Considering a rectangular distribution, corresponding standard uncertainty is 2.3⁄√3=1.3 µm.

Table 1. A list of all measured diameters by XCT in magnifications from 2.5× to 50×.

Magnification	Voxel (µm)	XCT, Mean Measured Diameter (mm)	Diff, XCT-Ref (µm)	Ref, Mean Diameter (mm)
2.5x	40	5.20955	7.1	5.1960
5x	20	5.20313	3.8	
10x	10	5.19979	2.3	
20x	5	5.19831	0.1	
25x	4	5.19607	0.2	
50x	2	5.19616	0.2	

3.6. Offset misalignment of the sample

Each time when placing the sample onto the rotating platform for XCT scanning, it is expected that the symmetrical axis of the sample is close as much as possible to the platform' rotating axis and the sample can be located nearby the centre area of X-ray cone beam. In this case, for a given X-ray spot size, there is a smaller edge error due to X-ray cone beam sharpness. To estimate a resulting error, a standard cylinder is placed in two positions aligned with and without a center offset by 1 mm, which can be easily aligned and controlled in the alignment using a 2D-axis translation stage in XCT. It found that there is a change of measured diameter by 1.1 µm. Considering a rectangular distribution, corresponding standard uncertainty is 1.1⁄√3=0.6 µm.

3.7. XCT repeatability performance and resolution

As an example, a solid cylinder sample with dimensions including widths and Heights (dimensions: 0.5 mm to 20 mm) is measured 5 time by XCT. The maximum standard deviation (1.4 µm) can be used to evaluate the repeatability and stability of the system as Type A standard uncertainty from a series of measurements. Based on the set of 5 measurements, the Type A uncertainty of the system due to random effects was found to be about 1.4⁄√5=0.62 µm. Considering a rectangular distribution of XCT's resolution: voxel size (10µm) with 1/10 interpolation, corresponding standard uncertainty is 1.0⁄√3=0.58 µm.

3.8. Analysis of measurement uncertainty

The uncertainty in XCT dimensional measurement can be addressed in accordance with the ISO Guide to the Expression of Uncertainty in Measurement (GUM) [9]. The uncertainty budget distinguishes between contributions of Types A and B, in which can be referred to those studied influencing factors from Section 3.1 to Section 3.7.

In accordance with GUM, the combined standard uncertainty attributed to the dimensions (*L*) is given by the root sum squared of all the uncertainty components.

$$u_c = \sqrt{(0.62^2 + 0.58^2 + 2.9^2 + 0.35^2 + 2.9^2 + 0.52^2 + 1.3^2 + 0.6^2)}$$

=4.5 µm

From the t-distribution table, $k \approx 2$ for $v_{eff} > 100$ at a confidence level of approximately 95%, the expanded measurement uncertainty is given by

$$U(L) = k.u_c = 2 \times 4.5 = 9.0 \text{ µm}$$

Therefore, the expanded measurement uncertainty of dimension *L* is 9.0 µm, estimated at a level of confidence of approximately 95% with a coverage factor *k*=2.

4. Conclusions

This paper describes an experimental approach to study an XCT dimensional measurement uncertainty by comparing to the dimensions measured by standard reference equipment including coordinate measuring machine and digital micrometer. 4 designs are in through-hole and solid cylinders and squares respectively and each design is fabricated in 3 materials (Stainless steel (SS), Titanium (Ti) and Inconel (IN). The dimensions are covering from 0.5 mm to 20 mm. Total 12 samples have been successfully measured by the proposed XCT. It is found that all maximum dimension deviation from reference values are below 10 µm. Besides the different shapes and materials effect to the XCT dimensional measurement, other main influence factors including XCT power (voltage & current), beam hardening, surface determination, magnification and sample position center offset misalignment are identified and the resulting measurement errors are quantified individually. Based on those errors as uncertainty contribution components and GUM, an uncertainty budget is worked out and the measurement uncertainty is estimated to be less than 10 µm or in an order of 1 µm. The proposed investigation method can be developed as a practical means to provide quantitative measurement uncertainty evaluation of XCT used in dimensional measurement. Not only for macro-scale dimensional measurement uncertainty evaluation, but also applicable to micro-scale surface roughness measurement performance by XCT applied in additive manufactured parts.

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