euspen's 15th International Conference & Exhibition, Leuven, Belgium, June 2015
www.euspen.eu

Effect of surface roughness on uncertainty of X-ray CT dimensional measurements of additive manufactured parts

Valentina Aloisi[1], Simone Carmignato[1], Enrico Savio[2]

[1]*Department of Engineering and Management, University of Padua, Stradella S. Nicola, 3, 36100 Vicenza, Italy*
[2]*Department of Industrial Engineering, University of Padua, via Venezia 1, 35131 Padova, Italy*

valentina.aloisi@dii.unipd.it

Abstract
Determination of measurement uncertainty for CT dimensional measurements is a difficult task due to the amount of complex error sources affecting the entire process chain. One of the critical aspects to deal with is the presence of error components that must be taken into account additionally. Surface roughness has a strong influence, causing a considerable increase of uncertainty especially for parts characterized by high surface roughness, such as additive manufactured parts. The paper shows the influence of surface roughness on measurement uncertainty calculated for repeated CT measurements and investigates the relation between tactile CMM and CT measurements. The possibility to substantially decrease measurement uncertainty by correcting roughness systematic effects is outlined.

Keywords: X-ray CT, dimensional measurements, measurement uncertainty, surface roughness

1. Introduction

Over the last years, X-ray CT field of application has evolved towards dimensional and geometrical measurements of industrial products [1]. However, lack of standardisation, and difficulties in quantification of measurement uncertainty are limiting its application in industry. CT process chain indeed is affected by numerous influence quantities which interact among themselves in a non-linear and complex way. One of the critical aspects to deal with in CT measurements is the high influence of surface roughness. Up to now, in literature, there are few studies concerning the influence of surface roughness. In [2] uncertainty is assessed for a workpiece with roughness value R_z in the order of 6 µm. Surface roughness effects are there quantified on the basis of averaged R_z measurements and assuming that the surface lies half within the part material. In [3] the authors estimate effects of less than a quarter of the maximum pick to valley height of the profile in the sampling length (R_z) for a workpiece with R_z up to 134 µm, however they state that this assumption needs to be further verified.

When scanning parts affected by higher surface roughness, the problem of how to treat roughness uncertainty contribution becomes more relevant, since assumptions made to quantify the effect of surface roughness may produce uncertainty statements that are not appropriate. In the present paper an experimental study based on repeated CMM and CT measurements on an industrial workpiece produced by Additive Manufacturing (AM) and characterized by R_z up to 125 µm is reported. The influence of surface roughness as a systematic component has been investigated. The results enable the correction of this effect and a significant decrease in the CT measurement uncertainty.

2. Determination of CT measurement uncertainty

At the state of the art, there are no internationally accepted standards for determination of measurement uncertainty for CT measurements. The set-up of a model equation, as outlined in the GUM [4], is not practically possible for CT systems due to the amount of complex error sources influencing the entire process chain. The experimental approach, outlined in ISO 15530-3:2011 [5] makes use of calibrated workpieces respecting similarity conditions with those for which measurement uncertainty must be evaluated. Expanded measurement uncertainty U is then determined through a series of repeated measurements, by equation (2.1):

$$U = 2 \cdot \sqrt{u_{cal}^2 + u_p^2 + u_w^2 + u_b^2} \qquad (2.1)$$

where u_{cal} is the calibration uncertainty of the calibrated workpiece, u_p the uncertainty of measurement procedure, u_w the uncertainty resulting from material and manufacturing variations (form errors, surface roughness etc.), and u_b the uncertainty of the systematic error.

For CT measurements, however, due to the multitude of error sources, in many cases it is extremely difficult to determine the single components of the systematic error b, and hence the associated uncertainty component u_b. Therefore, it is sometimes preferred to use uncorrected results and compute the uncertainty adding the bias contribution b directly to the uncertainty value, e.g. as it was suggested in ISO/TS 15530-3:2008 [6].

In [2] roughness uncertainty component is calculated for a workpiece with an average R_z of 6.82 µm, scanned with a voxel size of 145 µm. A rectangular distribution with limits ± $R_z/2$ is there assumed. This component is added to u_w which then contributes to U. If this assumption is applied also to measurement of parts characterized by high surface roughness, u_w can reach several tens of microns, giving a considerable overestimation of measurement uncertainty.

Moreover, if the bias b is added to the uncertainty budget, in case of relevant systematic errors, it could be the predominant component in the uncertainty budget. This is the case for parts characterized by high surface roughness. The different principle on which tactile measuring instruments and non-contact techniques rely on cannot be neglected indeed. Tactile CMMs, for example, acquire points by means of the mechanical contact between the probe stylus tip and the surface of the workpiece. The finite dimensions of the tip cause a mechanical filtering which increases with the dimensions. The profile acquired by means of tactile measurements, therefore, is shifted toward roughness peaks. On the other hand, CT measuring principle relies on the attribution of a medium grey level, according to the material attenuation and the path followed by the X-rays, to each voxel composing the 3-D model. While measuring parts characterized by a relevant surface roughness, therefore, systematic effects between tactile CMM measurements and CT measurements are expected. In this case, adding the u_w contribution coming from roughness as reported in [2] and the bias b to the uncertainty budget as well would produce a high overestimation of the measurement uncertainty.

3. Experimental investigation and results

To investigate the influence of surface roughness on CT dimensional measurements, a set of repeated measurements has been carried out on a steel part produced by Selective Laser Sintering (SLS), featuring internal and external cylinders with diameters from 40 mm to 90 mm. The workpiece was previously calibrated using a tactile CMM (MPE of length measurement: 2.7 + L(mm)/300 µm). Calibrated values of internal and external diameters of different dimensions where obtained through 10 repeated CMM measurements in scanning mode with approximately 1500 points, using a ruby sphere probe with a diameter of 3 mm.

Then 7 repeated CT scans of the part were performed with a voxel size of 120 µm. CT data were then analysed by means of VGStudio MAX 2.2, using advanced local threshold determination method. The same alignment conditions used for CMM measurements were replicated on the CT model. Each diameter was then measured by fitting a least square cylinder of 0.2 mm height on the CT model, to consider the zone in which the CMM probe, of finite dimensions, has acquired points.

Surface roughness was measured with a stylus measuring instrument using a 5 µm stylus tip. Values of R_z up to 125 µm were obtained. In this work, CMM measurements were considered as reference results; therefore, it was decided to attribute all the uncertainty due to roughness to CT measurements, to upper-bound CT uncertainty.

Experimental results are shown in **Figure 1**. CT measurements of external diameters are always smaller than CMM measurements, with a difference of approximately $R_z/2$. Symmetrically, CT measurements of internal diameters are larger than CMM calibrated values, with a difference of nearly $R_z/2$. After correcting the $R_z/2$ systematic error, a residual roughness uncertainty component $u_w = R_z/8$ can be estimated. This component is completely attributed to CT, to upper-bound CT uncertainty. An average reduction of more than 59 % of CT measurement uncertainty is obtained for internal diameters, reductions up to 85 % are obtained for external diameters.

4. Conclusions

The influence of surface roughness in CT measurement has been evaluated through repeated CT scans on an industrial part produced by SLS characterized by R_z up to 125 µm. Experimental results based on 49 CT measurements on diameters of different dimensions have shown that surface roughness causes a systematic shift between CT and CMM measurements. CT measurements on internal diameters are always larger than calibrated values whereas CT measurements on external diameters are always smaller than calibrated values, with a difference of about $R_z/2$. This difference can then be treated as a systematic component. A residual uncertainty coming from surface roughness $u_w = R_z/8$ can be estimated. This leads to a reduction ranging from 59 % to 85 % of CT measurement uncertainty.

Further studies will be conducted to investigate the relation between surface roughness and the dimensions of the voxel.

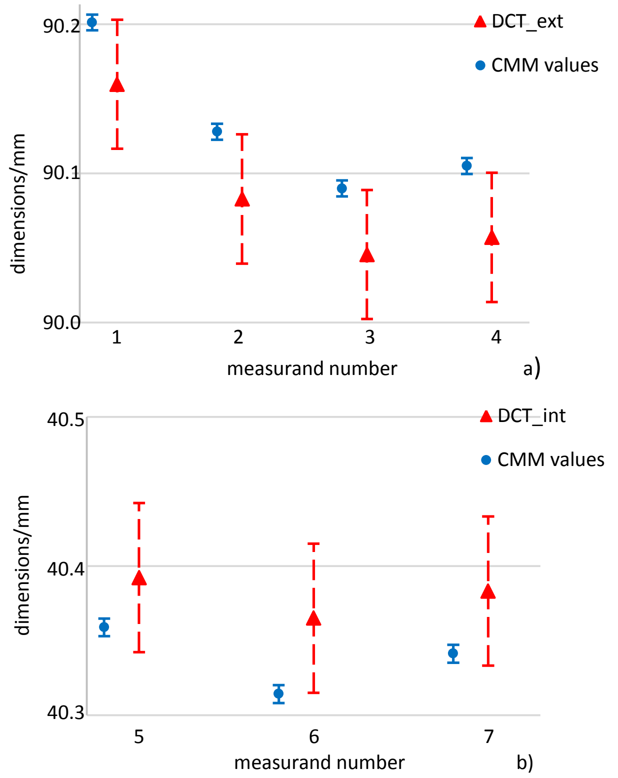

Figure 1. Effects of surface roughness on external a) and internal diameters b). Red triangles represent CT mean values of external ($DCT_{\_ext}$) and internal diameters ($DCT_{\_int}$). Dashed bars represent the $\pm R_z/2$ interval. Blue circles stand for CMM calibrated values, with associated error bars representing expanded calibration uncertainty.

References

[1] Kruth J P, Bartscher M, Carmignato S, Schmitt R, De Chiffre L and Weckenmann A 2011 Computed tomography for dimensional metrology *CIRP Annals-Manufacturing Technology* **60(2)** 821-842.

[2] Schmitt R and Niggemann C 2010 Uncertainty in measurement for x-ray-computed tomography using calibrated work pieces *Measurement Science and Technology* **21(5)** 054008.

[3] Bartscher M, Neukamm M, Koch M, Neuschaefer-Rube U, Staude A, Goebbels J, Ehrig K, Kuhn C, Deffner A and Knoch A 2010 Performance assessment of geometry measurements with micro-CT using a dismountable work-piece-near reference standard *Proc. Eur. Conf. on NDT (ECNDT 2010) Moscow*.

[4] JCGM 100:2008, Evaluation of measurement data - Guide to the expression of uncertainty in measurement.

[5] ISO 15530-3:2011, Geometrical product specifications (GPS) – Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement - Part 3: Use of calibrated work pieces or measurement standards. International Organization for Standardization, Genève.

[6] ISO/TS 15530-3:2008, Geometrical product specifications (GPS) – Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement - Part 3: Use of calibrated workpieces or measurement standards. International Organization for Standardization, Genève.