Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 75 (2018) 114–118

www.elsevier.com/locate/procedia

15th CIRP Conference on Computer Aided Tolerancing – CIRP CAT 2018

X-ray computed tomography for metal additive manufacturing: challenges and solutions for accuracy enhancement

Filippo Zanini[a]*, Elia Sbettega[a], Simone Carmignato[a]

[a]*Department of Management and Engineering, University of Padova, Stradella S. Nicola 3, 36100 Vicenza, Italy*

* Corresponding author. *E-mail address:* filippo.zanini@unipd.it

Abstract

Additively manufactured parts are characterized by metrological challenges and complexities, due to several reasons, including the inherent presence of internal defects and complex surface topography. Micro X-ray computed tomography is currently used to perform dimensional evaluations, porosity analysis and, more recently, surface topography measurements of additively manufactured parts thanks to the possibility of analysing non-destructively also non-accessible geometries and micro-scale features. However, the accuracy of these evaluations can be limited due to the high complexity of such parts. This work summarizes the results of experimental investigations on metrological challenges and accuracy of tomographic analyses, based on studies performed on Ti6Al4V specimens produced via selective laser melting.

Peer-review under responsibility of the Scientific Committee of the 15th CIRP Conference on Computer Aided Tolerancing - CIRP CAT 2018.

Keywords: X-ray computed tomography, dimensional metrology, additive manufacturing

1. Introduction

Additive Manufacturing (AM) of metals has the great potential of producing parts characterized by complex geometry and high structural complexity, with almost infinite design freedom [1]. State-of-the-art AM technologies, such as selective laser melting (SLM) and electron-beam melting (EBM), allow fabricating nearly full dense parts as well as strong and complex metallic lattice structures [2], which are impossible to be obtained through conventional manufacturing techniques (e.g. machining and casting) [3]. For these reasons, the interest of high-value sectors (e.g. aerospace [4]) for the opportunities provided by AM technologies is rapidly increasing. However, components used for such sectors must often meet tight dimensional and geometrical tolerances [5], which can be rather complex for AM parts, as additive technologies are inherently characterized by high variability [6] and many quality issues (e.g. poor geometrical accuracy, complex surface topography with high surface roughness and presence of internal defects). Micro X-ray computed tomography (CT) is an advanced measuring technique that can be effectively used for characterizing AM components [7, 8], as it is capable of examining non-destructively also macro- and micro-scale features that are inaccessible with other measuring techniques. Metrological CT systems are currently available to conduct accurate dimensional measurements [9] of both external and internal geometries. Moreover, internal defects (e.g. voids and inclusions) can be investigated in terms of size, spatial distribution and morphology [10]. Finally, more recently, CT has started to be considered as a viable alternative technique capable of obtaining topographical measurements at micro-scale, including non-accessible surfaces and re-entrant features [11, 12].

This work summarizes the results of experimental investigations on the accuracy of the CT-based evaluations introduced above, with regard to AM applications. The accuracy was investigated by two approaches: (i) comparison with other well-established measuring techniques and (ii) assessment of measurement errors using calibrated objects. Experimental analyses were performed on different SLM parts made of Ti6Al4V. Section 3 addresses the accuracy of CT dimensional evaluations performed on cellular specimens (i.e. CAD comparison and thickness analysis). Section 4 focuses

2212-8271
Peer-review under responsibility of the Scientific Committee of the 15th CIRP Conference on Computer Aided Tolerancing - CIRP CAT 2018.
10.1016/j.procir.2018.04.050

on the accuracy of CT surface topography measurements and Section 5 on the accuracy of CT porosity analysis.

2. Metrological CT system

All the CT measurements reported in this work were performed using a metrological CT system (Nikon X-Tek MCT225) equipped with a 225 kV micro-focus X-ray source, 2000×2000 flat panel detector (16 bit) and temperature controlled cabinet. The maximum permissible error for unidirectional length measurements is MPE = 9 + L/50 µm (L is the length in mm).

The acquired datasets were processed using the analysis- and visualization software VGStudio MAX 3.1 (Volume Graphics GmbH, Germany).

3. Dimensional evaluations

Dimensional measurements (e.g. length and diameter measurements) performed by CT are commonly based on least-squares fitting of geometrical elements. The surface roughness was determined to cause relevant systematic deviations between such CT measurements and tactile reference measurements [13]. This holds especially for highly rough parts (as the case of AM parts). Besides measurements based on least-squares fitting, another common CT dimensional evaluation is the comparison between measured part and nominal model (CAD comparison). This evaluation allows measuring the deviations between as-produced part and desired part mapping a large amount of points belonging to the specimen surface, which is important when particularly intricate structures (e.g. cellular specimens) are analysed. However, the deviations determined from the CAD comparison include both geometrical/dimensional errors and structural distortions (often present in AM complex structures [14]). For this reason, when the interest is on evaluating only the errors associated with the local dimensions, a thickness analysis is more effective. The influence of surface texture on the accuracy of both CAD comparison and thickness analyses performed on cellular structures were addressed in this section by experimental as well as by simulation investigations.

3.1. Experimental investigations

Cellular specimens with different lattice designs were produced by SLM of Ti-6Al-4V and scanned via X-ray computed tomography (voxel size equal to 8.3 µm).

Fig. 1-a illustrates the color-coded deviations between a CT-measured specimen and the corresponding nominal model. As demonstrated by Fig. 1-b, the investigated cellular structures present significant structural distortions which are included in the deviations determined from the CAD comparison.

A first thickness analysis was conducted using the default value proposed by the software (see Section 2) for the search angle (i.e. 30°). A peak of very low thickness was found for each specimen, as visible in Fig. 2 where two specimens (A and B) are taken as examples. The presence of these peaks was observed to be related to the complex topography of the surface with high form errors and high surface roughness. Sample A has a higher roughness than sample B, confirmed by *Sa* and *Sz* parameters (calculated as per the ISO 25178-2 [15]), from CT topographies of areas randomly selected inside the part on nominally cylindrical portions after the subtraction of a least-squares mean cylinder) which are 27 and 267 µm respectively for sample A, and 19 and 157 µm for sample B. The anomalous peaks were observed to decrease systematically by changing the search angle (e.g. systematic decrease of 70 % by changing the search angle from 30° to 15°) as shown in Fig. 2 for sample A.

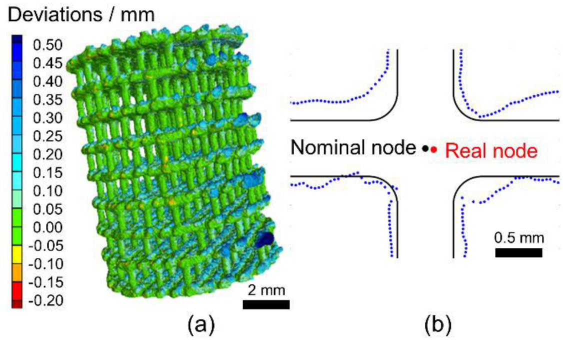


Fig. 1. (a) Color-coded map of deviations between CT-measured part and nominal model; (b) Real node (red point, obtained by CT data) compared with the corresponding nominal node (black point) of specimen C. Black lines represent the CAD model and blue dots represent the measured surface.

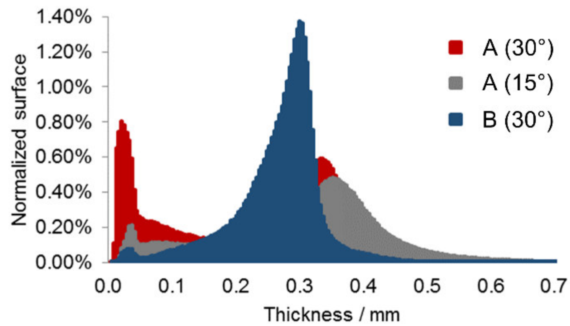


Fig. 2. Thickness distribution for samples A (thickness analysis performed with search angle 30° and 15°).and B (thickness analysis performed with search angle 30°).

3.2. Simulations

The combined influence of the surface topography and the search angle on the thickness analysis was analysed by simulating five cylindrical features (Ci, i=[1,5]) with different surface topographies and known thickness distribution (i.e. cylindrical features with height equal to 1 mm, obtained from the 360°-rotation of different sinusoidal functions around the central axis). Fig. 3 reports the percentage deviations obtained by comparing the measured mean thickness (weighted on the surface area interested by each thickness) with its corresponding reference value. The error related to the mapped surface (i.e. the surface actually analysed by the algorithm) is reported as well. The search angle 15° was determined to allow mapping well the surface while keeping deviations under 5%.

The same cylindrical features were used to investigate the influence of different surface topographies on the CAD comparison analysis. Errors below 2.3 % were obtained.

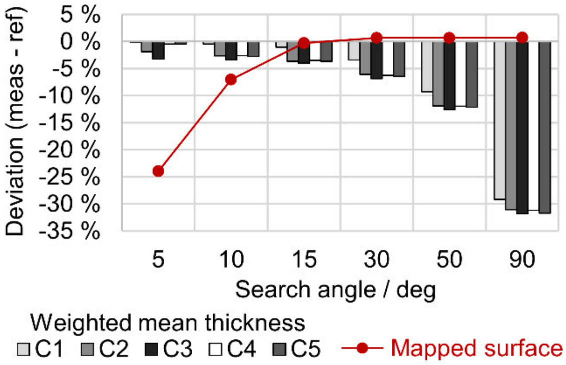
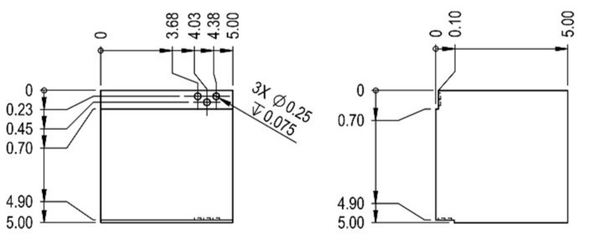


Fig. 3. Relative deviations (measured - reference) of the five simulated cylindrical features (C1,…,C5), concerning the mean thickness (weighted on the surface interested by each thickness) and the mapped surface, for different search angles.

4. Surface topography measurements

Traditional contact probing techniques can be used to measure the surface texture with low uncertainty [16]. However, when measuring AM surface topographies, reference measurements are not available as neither contact nor optical instruments are capable of acquiring the re-entrant features (typical of AM surfaces) and measuring inaccessible surfaces. Moreover, different optical techniques were proven to lead to substantially different results in terms of areal texture parameters [11]. This section presents an alternative approach for obtaining 2D reference surface profiles (including undercuts) to be compared with profiles measured by X-ray computed tomography as well as other non-contact techniques.

4.1. Experimental approach for accuracy evaluation



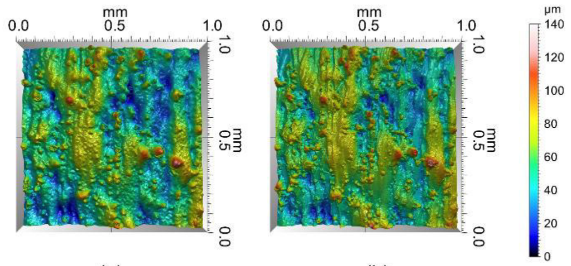
(a) (b)

Fig. 4. Technical drawing of the designed reference part: top (a) and side (b) view. Nominal values are reported in millimetres.

A specific reference sample geometry (see Fig. 4) was designed to enable the accurate alignment of 3D topographies and 2D profiles acquired with different instruments. After manufacturing the sample (Ti6Al4V selective laser melted parallelepiped with micro-milled markers), it was scanned by means of X-ray computed tomography.

Surface topographies were extracted from the obtained CT data and the topographies were acquired on the same surfaces by confocal microscopy (CM; Sensofar Plu Neox with a 20× objective characterized by NA equal to 0.45 and spatial period limit of 0.65 µm). Such topographies were aligned (first alignment based on the markers machined on the reference sample, followed by a fine cross correlation-based global algorithmic alignment) and compared in terms of areal texture parameters (S-parameters defined by the ISO 25178-2 [15]) after the subtraction of a least-squares mean plane (spatial frequency equal to 1 µm for all topographies). The next step consisted in cutting and polishing one face on the sample perpendicularly to the analysed surfaces, in order to allow imaging of actual cross-sectional profiles (including re-entrant features). Reference profiles were acquired using a multisensor coordinate measuring machine (CMM) equipped with imaging probing sensor (Werth Video Check IP 400; MPE = 1.8+L/250 µm, with L in mm). Another CT scan of the sample was performed after it was cut. By the alignment of topographies (CT, CM) acquired before the cutting/polishing procedure with the CT volume obtained after cutting/polishing, it was possible to identify exactly the same profiles measured using the CMM. In this way, the profiles acquired with CT and CM could be compared with the reference profiles in terms of ISO 4288 [17] parameters on the primary profile (P-parameters) after subtraction of the least-squares mean line, and – in case of presence of undercuts – in terms of area measured under each profile.

4.2. Results



(a) (b)

Fig. 5. Portions of aligned surface topographies acquired by means of: CT scanning (a) and confocal microscopy (b).

Table 1. S-parameters measured on CT and CM topographies.

Parameter	CT	CM
Sa	14.7 µm	14.8 µm
Sq	19.1 µm	19.0 µm
Ssk	-0.41	0.01
Sku	3.39	3.35
Sal	0.105 mm	0.105 mm

Table 2. P-parameters measured on profiles acquired by means of: CMM with imaging probing sensor (reference), CT and CM.

Parameter	Reference	CT	CM
Pa	16.2 µm	16.1 µm	17.0 µm
Pq	19.8 µm	19.6 µm	20.3 µm
Pz	81.6 µm	78.5 µm	79.0 µm
Psk	0.431	0.450	0.498
Pku	2.42	2.40	2.32

Fig. 5 compares two regions extracted from the aligned three-dimensional surface topographies acquired with CT (Fig. 5-a) and CM (Fig. 5-b). Table 1 reports the areal texture parameters, chosen according to the literature [11], calculated for comparing the employed measuring technologies. The results are similar (within 1 %) for both CT and CM evaluation of all the considered parameters, except for Ssk.

Two different portions of 2D profiles are shown in Fig. 6: one with no presence of re-entrant features (Fig. 6-a) and the other with more complex characteristics, including undercuts (Fig. 6-b).

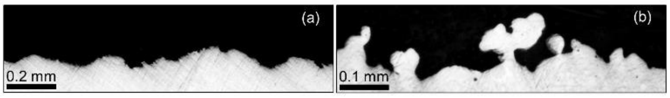


Fig. 6. 2D profiles imaged by CMM with imaging sensor on the cut-sections of the reference AM part. The first profile does not present any re-entrant feature (a), while the other shows several undercuts (b).

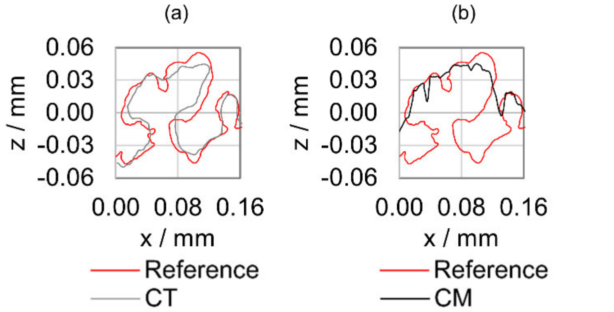


Fig. 7. 2D profiles containing undercuts measured using: CT (a) and CM (b). Both profiles are compared with the reference profile (in red), measured using CMM with imaging probing sensor.

The first profile (Fig. 6-a) can be analysed as a conventional roughness profile: the P-parameters measured by CT and CM are compared with the reference parameters in Table 2.

Concerning the second profile (Fig. 6-b), Fig. 7-a shows that CT is capable of acquiring information also about undercuts over the analysed surface, while Fig. 7-b shows how CM is limited to non-recessed surfaces. Profiles and surfaces containing undercuts cannot be used to calculate conventional roughness/areal texture parameters [18]. For this reason, the profiles in Fig. 7 were compared by measuring the areas under each investigated profile. A difference of 8 % (negative) was obtained between CT and reference measurements, while for the CM the difference was of 46 % (positive).

5. Internal defects analysis

CT porosity analysis has been compared in literature with other well-established inspection techniques such as Archimedes method and microscopic analysis [19,20]. However, reference porosity measurements were not available in these works, although they are necessary for measurement errors assessment. This section is focused on (i) comparing the results obtained by the inspection techniques mentioned above with reference values for dimensions of pores visible in cross-sections and (ii) using a reference object with calibrated artificial hemispherical defects designed and manufactured in order to quantify typical errors of CT porosity measurements.

5.1. Comparison of porosity evaluation methods

The comparison has involved experiments on Ti6Al4V specimens produced by SLM with different process parameters and, consequently, different porosity content. Relative densities determined by the Archimedes method were found to be systematically 0.2 – 0.4 % lower than the corresponding CT values. Causes of this difference can be attributed both to: (i) Archimedes' relative density determination is based on the nominal material density, which however is not reliable for non-homogeneous parts, (ii) CT results are influenced by image artefacts due to the interaction between X-rays and material, by the achieved resolution in the CT reconstruction (e.g. pores with size lower than the spatial resolution cannot be detected) and by the thresholding procedure. In addition, a new procedure was developed for comparing results by microscopic analysis of cross-sections with CT results: specimens were CT scanned before and after the cutting procedure, in order to (i) identify in the CT volume the exact cross-section analysed for the comparison and (ii) to compare CT results obtained before and after cutting the samples. To obtain reliable reference values, the areas of specific pores lying on the cut-section were measured using the image processing sensor of the CMM Werth Video-Check-IP 400. The results by microscopic analysis of cross-sections were found to be close to the CMM results, while CT always measured smaller areas (Fig. 8). Besides the aforementioned CT main influences, the systematically lower areas measured by CT post-cut with respect to CT pre-cut reveal other two possible causes: (i) deformations due to cutting/polishing operations and (ii) presence of entrapped non-totally melted powder residue that may fall out during the cutting.

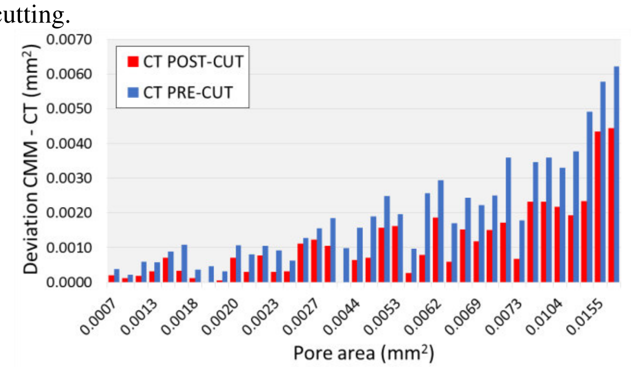


Fig. 8. Example of deviations between pore areas measured by multisensor CMM and CT (pre and post cut) on Ti6Al4V specimens.

5.2. Errors evaluation in CT porosity measurements

Errors in CT porosity measurements were evaluated using the reference object with artificial defects presented in [21]. The object is made of aluminium and contains hemispherical features with diameters ranging from 100 µm to 500 µm resembling real internal voids/porosity. Its dismountable configuration allowed external dimensional calibration of the artificial defects using coordinate measuring systems. Experimental investigations using the newly developed reference object proved that for optimal CT parameters settings, the errors can be below 5 µm in case of diameter and below 5 % for volume measurements. However, the errors in case of smaller defects (smaller than 0.200 mm in diameter) are higher, as shown in Fig. 9 for the volume measurements.

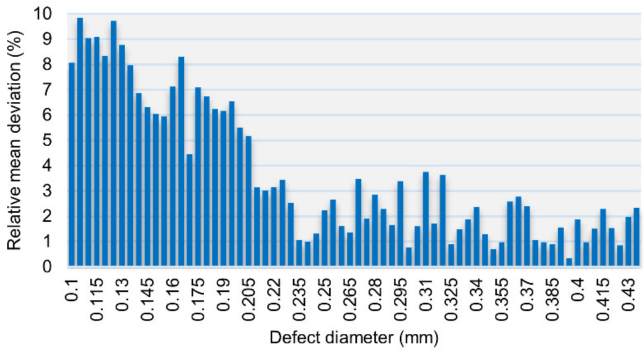


Fig. 9. Example of CT porosity measurement errors evaluation using the newly designed reference object.

6. Conclusions

The accuracy of CT-based evaluations of AM components has been addressed in this paper. Experimental investigations - performed on different SLM parts made of Ti6Al4V - were focused on: dimensional evaluations (CAD comparison and thickness analysis), surface topography measurements and internal defects analysis. It was discussed how the CAD comparison analysis can be influenced by structural distortions which can often occur in complex additive manufacturing parts, but it was determined to be less influenced by the surface topography than the thickness analysis. The thickness analysis was found to be sensitive to the surface quality and the search angle. The search angle was optimized by evaluations performed on simulated cylindrical features with varying surface topography and the thickness analysis of SLM specimens was then improved. In addition, a new approach and a new reference sample are proposed to evaluate the accuracy of CT surface topography measurements. Reference cross-sectional profiles (including undercuts) were measured using a CMM equipped with imaging probing sensor, after cutting the samples at specific locations. CT was determined to be capable of acquiring surface profiles (containing also re-entrant features) with small deviations (8 % maximum difference in terms of areas, for the investigated case) with respect to the reference profiles. The proposed methodology will be used in future for determining the uncertainty of CT surface topography measurements through the application of the substitution method [22]. Finally, CT porosity measurements were compared with the Archimedes method (CT densities systematically higher by 0.2 – 0.4 % than Archimedes densities) and with the microscopic analysis of cross-sections (CT measured pore areas always smaller than optically measured areas). The investigation using the reference object with calibrated artificial defects for errors evaluation of CT porosity measurements has shown that for larger pores it is possible to evaluate internal porosity with measurement errors below 5 µm for diameter and below 5 % for volume measurements.

Acknowledgements

The author would like to thank Dr. Petr Hermanek (University of Padova), Dr. Marco Sorgato (Univesity of Padova) and Prof. Matteo Benedetti (University of Trento).

References

[1] Levy GN et al. Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, State of the art and future perspectives. CIRP Annals Man. Tech. 2003; 52(2) 589-609.
[2] Yan C et al. Evaluations of cellular lattice structures manufactured using selective laser melting. International Journal of Machine Tools & Manufacture 2012; 62 32-38.
[3] Beyer C, Figueroa D. Design and analysis of lattice structures for additive manufacturing. Journal of Manufacturing Science and Engineering 2016.
[4] Orme ME et al. A Holistic Process-Flow from Concept to Validation for Additive Manufacturing of Light-Weight, Optimized, Metallic Components Suitable for Space Flight. 58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference; 2017.
[5] Savio E et al. Metrology of freeform shaped parts. CIRP Annals Man. Tech. 2017; 56(2), 810-835.
[6] Sharratt BM. Non-destructive techniques and technologies for qualification of additive manufactured parts and processes. A literature review. Contract Report; 2015.
[7] Thompson A et al. X-ray computed tomography for additive manufacturing: a review. Meas. Sci. Technol. 2016; 27(7), 072001.
[8] Khademzadeh S et al. Precision additive anufacturing of NiTi parts using micro direct metal deposition Int. Journal of Advanced Manufacturing Technology 2018.
[9] Carmignato S et al. Industrial X-ray Computed Tomography. Springer International Publishing 2018. ISBN 978-3-319-59571-9
[10] Wits WW, et al. Porosity testing methods for the quality assessment of selective laser melted parts. CIRP Annals Man. Tech. 2016; 65(1).
[11] Thompson A et al. Topography of selectively laser melted surfaces: A comparison of different measurement methods. CIRP Annals Man. Tech. 2017; 66.
[12] Townsend A et al. Areal Surface Texture Data Extraction from X-ray Computed Tomography Reconstructions of Metal Additively Manufactured Parts. Precision Engineering 2017; 48 254-264.
[13] Carmignato S et al. Influence of surface roughness on computed tomography dimensional measurements. CIRP Annals Man. Tech. 2017; 66.
[14] Martz HE et al. CT to evaluate of distortions in stainless-steel AM structures Proc. of ASPE Spring Topical Meeting 57; 2017.
[15] ISO 25178-2 GPS—Surface Texture: Areal—Part 2: Terms, Definitions and Surface Texture Parameters; 2012.
[16] Whitehouse DJ. Surfaces and their measurement London: Hermes Penton Science 2002.
[17] ISO 4288 GPS—Surface Texture: Profile method—rules and procedures for the assessment of surface texture; 1996.
[18] Pagani L et al. Towards a new definition of areal surface texture parameters on freeform surface. Measurement 2017.
[19] Ziolkowsi G et al. Application of X-ray CT method for discontinuity and porosity detection in 316L stainless steel parts produced with SLM technology. Arch. Civ. Mech. Eng. 2014; 14 608-614.
[20] Spierings AB. Comparison of density measurement techniques for additive manufactured metallic parts. Rapid Prototyping Journal 2011; 17(5) 380.
[21] Hermanek P, Carmignato S. Porosity measurements by X-ray computed tomography: Accuracy evaluation using a calibrated object. Precision Engineering 2017; 49, 377-3.
[22] VDI/VDE 2630-2.1 Computed tomography in dimensional measurement – Determination of the uncertainty of measurement and the test process suitability of coordinate measurement systems with CT sensor; 2015.