Porosity measurements by X-ray computed tomography: Accuracy evaluation using a calibrated object

Petr Hermanek*, Simone Carmignato

University of Padova, Department of Management and Engineering (DTG), Stradella San Nicola 3, 36100 Vicenza, Italy

A R T I C L E   I N F O

Article history:
Received 20 December 2016
Received in revised form 22 March 2017
Accepted 30 March 2017
Available online 4 April 2017

Keywords:
X-ray computed tomography
Dimensional metrology
Reference object
Internal defects
Simulations

A B S T R A C T

Accurate identification and measurement of internal voids and porosity is an important step towards improvement of production processes to obtain high quality materials and products. Recently, the importance of knowing the exact size, shape, volume and location of defects has become even higher as tighter requirements and new standards have been introduced in industry. There are several well-established methods for defects evaluation based on various principles (both destructive and non-destructive). However, all conventional methods have various deficiencies and the information about internal voids/porosity that can be extracted is limited. Most of these drawbacks can be overcome by using X-ray computed tomography (CT). Unlike other methods, CT provides full three-dimensional information about shape, size and distribution of internal voids and porosity; however, the accuracy of measurements is still under investigation. Hence, further evaluations on CT porosity measurements must be performed in order to consider X-ray computed tomography a reliable instrument for the assessment and detection of internal defects.

A reference object with artificial defects was used in this research work in order to evaluate the accuracy of porosity measurements by CT. The reference object was manufactured by ultra-precision micromilling. The object contains dismountable components with embedded internal hemispherical features that simulate internal porosity. The artificial porosity was micro-milled on top surfaces of dismountable cylindrical inserts. The hemispherical calottes were thereafter calibrated by traceable coordinate measuring systems and calibrated values were compared to actual values measured by a CT system. The accuracy of CT porosity measurements was then evaluated based on results obtained on various measurement procedures, using different software tools and measuring procedures, comparing real scans to numerical simulations and investigating the influence of CT system. The results obtained are presented in the paper.

© 2017 Elsevier Inc. All rights reserved.

1. Introduction

Internal defects such as voids and porosity are an inherent part of many manufacturing processes such as casting, injection moulding, additive manufacturing (AM), composite materials fabrication etc. [1–6]. The amount of internal defects has direct influence on degradation of industrial parts and material characteristics [7,8]. As the internal flaws cannot be completely eliminated due to the nature of production processes and significant cost increments, it becomes very important to measure them accurately [5]. The importance of accurate porosity evaluation has recently increased with release of new standards and guidelines regarding porosity measurements, e.g. VDG P 201 [9]. Several studies on total porosity content in volume and its influence on mechanical properties were performed [7,10,11]. Recent investigations [12], however, have shown that the global percentage view can be too simplistic and, therefore, shape, size and distribution of internal defects must be considered [12,13].

Various non-destructive and destructive methods for porosity determination are applied in various applications. Among the most established and reliable techniques belong ultrasonic testing, Archimedes method and materialography. However, in case of ultrasonic testing, the extraction of 3D information about internal voids/porosity is rather difficult. Furthermore, the accuracy of measurements can be influenced by non-homogeneous size and distribution of defects [2,14]. Archimedes method, on the other hand, provides just the total void fraction which misses the information about size, shape and distribution of defects completely [3,15]. The drawback of materialography consists in several
attributes: the method is destructive, usually time consuming, the results are highly dependent on the quality of sample preparation and the limited number of analysed cuts can result, in case of non-homogenously distributed defects, in wrong porosity content assessment [3].

X-ray computed tomography has been widely used in non-destructive testing of products manufactured by various technologies including casting, additive manufacturing and others [16]. Recent advances proved CT to be a promising technique for advanced internal porosity detection and characterization [17,18]. During a CT scan in a 3D cone beam CT system, which is commonly used in industry, the sample is placed on the rotary stage between the X-ray source and detector. During the rotation of the sample, a number of images (2D radiographs) is acquired. Thereafter, a reconstruction algorithm is applied to reconstruct the acquired images into a 3D volume dataset composed of voxels (3D pixels). CT datasets include information about the sample structure and composition, density distribution, internal and external shape, etc. [19]. By applying segmentation algorithms, e.g. by setting a grey value threshold, air can be separated from solid material and information about internal porosity can be extracted. The data provided by CT volumetric representation of the sample include all the important attributes such as defect size, shape and volume, as well as total void content and distribution within the inspected volume.

Recent demands on porosity measurements require a metrological validation method, which is still under development. A reference object with artificial defects is used in this publication for the accuracy investigation of porosity measurements by CT. Several reference objects have been used in literature focused on measurements of internal defects. Nikishkov et al. [6] aimed on material/void segmentation improvement, which is one of the critical points in voids/porosity measurements. A reference object with micro holes was used in their publication and CT measurements were compared to measurements obtained by microscopy. Nevertheless, the micro holes were accessible from the surface and, therefore, did not simulate real internal defects. Furthermore, the selected measuring was a circle measured in cross-sections, which did not provide any volumetric information about measurements. Jansson et al. [20] designed a reference object with macro and micro features for a study on additive manufacturing process and CT measurements accuracy. The measurements were performed on both external and internal features. However, the internal features were not measured by any other measuring system than CT as they were enclosed in the material. Therefore, the authors relied on the stability of the manufacturing process.

In a previous investigation by the same authors of the present paper [21], a reference object with embedded internal features resembling real internal defects was developed. In the present work, the reference object has been redesigned and improved based on deficiencies discovered in the previous investigation, and then the object has been used to study CT porosity measurements. The object is composed of a cylindrical body and four removable cylindrical pins with milled hemispherical features of calibrated size on their top faces. The object is described in Section 2 below. The previous study [21] proved that porosity assessment based only on diameter and depth measurements of defects is insufficient, especially when the shape of the defects is complex (as common for many manufacturing processes). Therefore, diameter and depth measurements were supplemented by volume measurements in this paper. Furthermore, the calibration of the hemispherical features has been improved in the present work, by integrating measurements from different measuring systems (see Section 2.2). Subsequently, the assembled reference object was scanned under different conditions and, hence, the influence of CT parameters settings on measurement accuracy was evaluated (see Section 3). Furthermore, as part of this work, additional investigations were carried out: repeated measurements were performed to analyse the repeatability, different software tools were used for porosity evaluation and results from real CT scans were compared to results from simulations. Conclusions are then drawn in Section 4.

2. Reference object

The reference object was designed taking into account all constrains from both the manufacturing and the application point of view. The object is made of an aluminium alloy 6005A, which ensures easy penetration by X-rays and at the same time good machinability and metrological stability. Aluminium was chosen also because it is typical of many manufacturing applications (such as casting processes) in which the products are affected by porosity. The dismountable design of the object allows for calibration of the internal artificial defects. These artificial defects are milled as hemispherical calottes into the top plane of inserts, which are then assembled together with the main body of the object to form internal features resembling pores of hemispherical shape.
2.1. Design

The geometry of the reference object is shown in Fig. 1. The cylindrical body has a diameter of 15 mm and a height of 23 mm, and contains four holes (Ø 5.1 mm) of different depths for placing cylindrical inserts with hemispherical calottes (artificial defects). The varying depths of the cylindrical openings make the distribution of defects more spread within the object’s volume. The size range of hemispherical features milled into the pins faces is from 100 μm to 500 μm, with eighteen features per pin, which results in 72 artificial defects in total. In order to avoid pins from being stuck in the holes and to facilitate fitting at the interface between the hole bottom and pin face, a 0.05 mm gap was left between the components. In each pin, the defects are arranged along two concentric circumferences with diameters 2 mm and 3.5 mm. Furthermore, two additional defects are placed on each pin; the first is placed in the center of a pin and the second (denoted as “Marker” in Fig. 1) is located outside the two circumferences and – by breaking the symmetry – ensures unambiguous identification of the defects.

Since the old design used in the previous work [21] suffered from instability of the pins position during scanning and movement, an improvement in form of polymer screws generating pressure on pins was implemented in this new version of the object. Furthermore, soft rubber washers for better pressure distribution were put between the screws and pins.

The stability of the assembly was documented by repeated CT scans, including scans acquired right after the assembly, after two months from the assembly and after disassembling and reassembling the sample after approximately one year. The average deviations between measurements obtained on individual scans were within the range of repeatability (below 1.5%) including the measurement of volume V, which is the most critical measure in terms of the stability of the assembly.

2.2. Manufacturing and calibration

The main parts (cylindrical holes, faces of pins and calottes) were manufactured by an ultra-precision 5 axis machining center (Kugler Micromaster 5X). The machining center was equipped by an aerostatic bearing and micro milling tools of diameters Ø 100 μm and Ø 250 μm. The manufacturing process in case of the old design [21] started with finishing of the pin top surface followed by milling of hemispherical calottes. This sequence of machining steps, however, caused burrs on edges of the calottes depicted in Fig. 2a. Even though the height of these burrs was in range of units of μm, the fitting of the hole bottom and the corresponding pin face was not tight enough. Therefore, the new version of the reference object was manufactured with a reversed order of machining steps. In a first step, the calottes were milled with a machining allowance and in a second step, this allowance was removed achieving good quality of the top surface and no burrs on calotte edges (Fig. 2b).

Calibration measurements were performed using three different measuring systems: (i) 3D optical profiler using confocal scanning, (ii) multisensor coordinate measuring machine (CMM) equipped with image processing sensor, and (iii) metrological CT system used at high magnification (40×, which corresponds to the voxel size of 5 μm). The calibration CT scans were obtained by scanning single pins covered by a counterpart with flat surface. The overview of instruments, methods and magnifications used for calibration is given in Table 1.

Furthermore, in order to ensure the traceability of measurements, several calottes were measured using a μ-CMM Zeiss F-25 with maximum permissible error (MPE) equal to (0.25 + L/666) μm (where L is length in mm). The subsequent traceability of measurements obtained by the instruments presented in Table 1 was established by applying the substitution method, determining the measurement uncertainty using a procedure derived from ISO 15530-3 [22,23]. The measurement uncertainties attributed to the calibration measurements are summarized in Table 2.

The old version of the reference object [21] was calibrated just by means of the 3D optical profiler and the multisensor CMM. However, the results showed that the 3D profiler cannot acquire sufficient number of points for accurate measurements in case of small defects (e.g. with diameter of 100 μm) because of steep surfaces. Furthermore, in [21] it was proved that diameter and depth calibrations are not sufficient for accurate determination of defects’ volume. Therefore, in this work also the volume of each defect was calibrated, using CT measurements at high magnification, with traceability established through comparison with optical measurements on defects’ diameters and depths.

2.3. Measurands and measurement strategies

The measurands evaluated in this publication are defined in Fig. 3: (i) diameter of a defect D, (ii) depth of a defect Z and (iii)

Table 1
Overview of calibration instruments.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Method</th>
<th>Magnification</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D optical profiler Sensofar Plu Neos</td>
<td>Confocal scanning of single calottes</td>
<td>20×</td>
</tr>
<tr>
<td>Multisensor CMM Werth Video Check IP 400</td>
<td>Measurement of the diameters of single calottes</td>
<td>9×</td>
</tr>
<tr>
<td>Metrological CT system Nikon Metrology X-Tek MCT 225</td>
<td>Measurement of defects volume in pins covered by a counterpart</td>
<td>40×</td>
</tr>
</tbody>
</table>

Table 2
Calibration measurement uncertainties.

<table>
<thead>
<tr>
<th>Measurand</th>
<th>Measurement uncertainty U_{\text{cal}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter D</td>
<td>2.1 μm</td>
</tr>
<tr>
<td>Depth Z</td>
<td>1.4 μm</td>
</tr>
<tr>
<td>Volume V</td>
<td>1.6% of the calotte volume</td>
</tr>
</tbody>
</table>
3. CT measurements and results

The accuracy of CT porosity measurements was evaluated according to several investigations discussed in this section:

1) Influence of CT parameters settings on measurement errors.
2) Repeatability of measurements.
3) Different approaches to volume measurements.
4) Comparison between measurement results obtained from simulated and real CT data sets.
5) Comparison of different evaluation software.

CT datasets were acquired by a metrological CT system, Nikon Metrology X-Tek MCT 225, used at low magnification (18.4×), which corresponds to the voxel size of 11 μm. The maximum permissible error (MPE) of the system is (9 + 1/50) μm (where L is length in mm). The data was processed and analysed using software VGStudio MAX 2.2.6 (Volume Graphics, Germany) except for analyses described in Section 3.5, where Volume Player (Fraunhofer EZRT, Germany) and iAnalyse (University of Upper Austria, Austria) software tools were applied.

Each CT dataset was evaluated following the same procedure in order to ensure the consistency of measurement results. The workflow is described as follows:

1) Loading the dataset and determination of surface using the local adaptive method with noise removal to reduce potential noise inside the defects.
2) Alignment of the dataset and segmentation of the volume in order to remove the calotte edge points for the measurement of defects diameter D.

3) Fitting of measuring elements, i.e. least squares spheres and planes, and measurement of defects diameter D and depth Z.
4) Evaluation of defects volume V using Defect analysis module and “Only threshold” algorithm embedded in VGStudio MAX.
5) Exporting the measurement results.

3.1. Influence of CT parameters settings on measurement errors

In setting up a CT scan, several factors depending on operator's choice influence final image quality and thus 3D volume dataset itself. Based on prior research [21,24], where voltage U and current I were identified as the most important influencing factors after magnification, four levels of U and I were chosen and Design of Experiments (DoE) technique was applied to study their influence. Magnification is not considered in this paper as its influence was already thoroughly investigated in other studies [22-26] with conclusion that with higher magnification, higher accuracy is achieved. The scanning parameters are shown in Table 3. The range of parameters was chosen with regards to obtain sufficient power to penetrate the sample with the lowest settings and at the same time not to saturate the detector using the highest settings.

Results of DoE are shown in Fig. 4. The analysis was performed for all the 72 defects; however, the plot would be illegible if the complete results were shown. Therefore, simplified charts with four representative examples are plotted in Fig. 4, respectively for small (Ø 110 μm), two medium (Ø 160 μm and Ø 240 μm) and large (Ø 400 μm) defect size.

Results in Fig. 4 show that the higher are the values of voltage and current, the lower are deviations from reference values for all the three characteristics, including volume V. Furthermore, use of CT reference values eliminated differences in deviation trends between larger and smaller defects that were observed in previous investigation [21]. The difference in magnitude between D and Z deviations (difference between Fig. 4a and Fig. 4b) demonstrate that errors are lower for depth measurements than for diameter measurements. Another observation that can be extracted from Fig. 4 is that measurements of smaller defects are more problematic (as the deviations are higher for all the three characteristics) than for larger defects. However, apart from D measurements of the smallest defects, the deviations are within ±5 μm, which shows good performance in porosity measurements.

Results plotted in Fig. 4 shows that the choice of scanning parameters has significant influence on the accuracy of porosity measurements, especially for defects below 160 μm. In case of the smallest defects, in fact, the variation caused by voltage and current settings is approximately 4 μm for D and Z measurements and around 3% for volume evaluation. The larger are the defects, the lower is the influence of U and I on measurement errors, as for Ø 400 μm defects the variation is below 1 μm for D and Z and below 1% for V measurements.

Another proof that higher values of current and voltage have a positive influence on measurement errors can be seen in Fig. 5. The chart shows the dependency of the average volume measurement deviations for all 72 defects on U and I settings. It can be observed that the average deviation decreases from 6.7% for the lowest settings, down to 2.4% for the highest settings.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Scanning parameters for DoE.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nr.</td>
<td>1</td>
</tr>
<tr>
<td>Voltage U/kV</td>
<td>130</td>
</tr>
<tr>
<td>Current I/μA</td>
<td>30</td>
</tr>
<tr>
<td>Voxel size/μm</td>
<td>10.9</td>
</tr>
<tr>
<td>Exposure time/ms</td>
<td>2829</td>
</tr>
<tr>
<td>Filter</td>
<td>0.25 mm Cu</td>
</tr>
<tr>
<td>Number of projections</td>
<td>1800</td>
</tr>
</tbody>
</table>
Fig. 4. Influence of CT parameters settings on measurement deviations; a) absolute value of $D$ deviations from reference values, b) absolute value of $Z$ deviations from reference values, c) absolute value of relative $V$ deviations from reference values.
Fig. 5. Dependency of relative mean volume deviation on current and voltage settings. Error bars represent mean standard deviation of repeated scans calculated over all 72 defects.

It is worth noting that the scans were performed using low tube power (below 8 W) and, therefore, it was possible to maintain the focal spot size at 3 μm. Hence, by keeping the focal spot size at the lowest level, the effect of investigated parameters \((U, I)\) was isolated.

There are two main explanations on why the positive trend of increasing voltage and current on measurement errors was observed:

1) The amount of noise in acquired projections is related to the amount of X-ray radiation, which is directly dependent on the tube current. If all the CT parameters are kept constant, the image noise scales roughly inversely proportional to the square root of the tube current [27,28]; i.e. by increasing the tube current, lower amount of image noise, and thus higher signal-to-noise ratio (SNR) can be achieved.

2) The dependency of conversion rate between the electrons accelerated in an X-ray tube and X-rays is different for current and

Fig. 6. Repeatability of measurements represented by ± 1 standard deviation error bars superimposed onto the histogram of mean value of deviations: a) deviations of diameter \(D\) measurements, b) relative deviations of volume \(V\) measurements.
voltage. While the dependency on current is linear, the generation of X-rays increases square with the tube voltage according to the equation $i \propto U^2I$, where $i$ is the X-ray intensity, $U$ and $I$ are the X-ray tube voltage and current, respectively, and $Z$ is the atomic number of the target. In other words, by increasing the tube voltage and, therefore, the energy of X-rays, a square-law X-ray output is generated with only linear increase of the tube power. Because of this behaviour, one can achieve lower amount of noise and higher contrast in acquired projections [29].

### 3.2. Repeatability of measurements

During scanning, a CT system is influenced by various factors, such as thermal instability, scattering, focal spot drift, etc. [21], which have impact on the repeatability of CT measurements. These effects directly influence the quality of acquired images and subsequently the reconstructed volume as well. In this paper, the stability of the investigated CT system was evaluated based on results of repeated measurements. 12 scans with the same set of CT scanning parameters were acquired during the DoE batch scan described in the previous section. The optimal scanning conditions resulting in highest measurement accuracy were chosen based on the prior investigation.

Results in Fig. 6 shows mean deviations for each of the 72 defects supplemented by ±1 standard deviation. Only errors of diameter and volume measurements are plotted in the charts, while depth measurements were omitted as they follow the same trend as in the previous research presented in [21] (reference values for depth measurements from 3D optical profiler applied in [21] did not suffer from lack of acquired points as diameter measurements did). Values of mean deviation shown in Fig. 6a demonstrate good performance of CT in porosity diameter measurements as, apart from 2 cases, the deviation is below ±5 μm. Furthermore, compared to the prior investigation [21], deviations of smallest defects were reduced using CT reference measurements at high magnification. Nonetheless, measurement errors for smaller defects are still higher (close to ±5 μm) than for larger defects (less than ±1 μm), which confirms the previous observations; i.e. measurements of smaller defects are more problematic. This trend is confirmed also by values of standard deviation, which ranges from 11 μm for smaller defects, to less than 1 μm for larger defects.

The dependency that can be observed in Fig. 6b shows a positive trend in deviations of volume measurements. In other words, the defects measured in assembled object at lower magnification (voxel size = 11 μm) appear to be larger than at higher magnification (voxel size = 5 μm) where the calibration was performed. This behaviour is in agreement with results of relevant publications [22,25,26] and is caused by averaging due to decreasing voxel size, lower sharpness of CT data and decrease of information content with decreasing magnification. Relative deviations of defects below 200 μm are lower than 10% and lower than 5% for defects above 200 μm. Hence, also results of volume measurements are in agreement with the observation that measurements of small defects are more problematic.

### 3.3. Different approaches to volume measurements

In this section, the volume of defects was evaluated according to two different strategies: (i) Defect analysis module embedded in the evaluation software VGStudio MAX and (ii) calculation based on Z and D measurements. The former defect analysis was carried out
using “Only threshold” algorithm in VGStudio MAX, which is completely based on the defined threshold value. The threshold value was chosen using “ISO50” method, which represents the average grey value between the material and the background peak. The latter procedure is based on volume calculation of a fitted hemisphere supplemented (or reduced) by volume between the top plane and the center of the referred sphere. The measuring elements in the case of calculation based on Z and D measurements were fitted on a surface determined using local adaptive thresholding.

Fig. 7a illustrates the comparison of the two measurement procedures. Defects were sorted into 14 groups according to their size. Results of the comparison show that the Defect analysis module calculates results with lower relative deviation compared to the values calculated from D and Z. The most significant difference can be observed in smallest defects, while as the defect size increases, deviations of the methods are equalizing. The reason for larger deviations between the methods in case of smaller defects is higher form error, which makes the calculation based on fitted features less accurate. The different effect of form errors on measurement errors can be observed in Fig. 7b, c. Compared to the feature-based calculation procedure, the volumetric Defect analysis is independent from fitted elements and thus also from form errors. Therefore, the Defect analysis method is more suitable for defects of an irregular shape. This fact is very important for industrial applications as real defects are usually of a random shape (i.e. far from spherical shape with low form error).

3.4. Comparison between measurement results obtained from simulated and real CT data sets

In addition to real CT scans, numerical simulations with extended range of voltage and current were performed in order to validate the results acquired on the real CT data sets. The CT data were simulated using the software “Analytical RT Inspection Simulation Tool” (“aRTist”, developed by BAM, Germany). The simulations were performed using the same parameters as listed in Table 3 supplemented by five additional voltage/current combinations listed in Table 4. In order to isolate the effects of current and voltage, all other parameters were kept unchanged for all the simulation runs. The focal spot size was set to 3 μm, which corresponds to the estimated focal spot size of the real CT scans.

The results in Fig. 8a–c show that the effect of voltage and current on the simulated data is similar to the trends observed in real CT datasets; i.e. the higher are the values of U and I, the lower are the measurement errors. Furthermore, similarly to real CT scans, measurements of smaller defects introduce higher measurement errors. Chart in Fig. 8d shows in addition relative mean deviations of volume measurements; i.e. mean measurement errors over all 72 defects for each voltage/current combination. The results confirm previous observations about the positive effect of increasing U and I settings on measurement errors. It must be noted that the magnitude of deviations is lower than that of the real data. This is caused by neglecting in simulated data some of the effects that are actually present in real CT scans such as geometrical instability of the system, focal spot drift, etc.

3.5. Comparison of different evaluation software

In previous sections, VGStudio MAX was used for the assessment of internal defects as it is well-established in industrial CT applications. However, the increasing importance of the accurate evaluation of internal defects drives the need for new software tools that are being developed. In this section, results of volume measurements from VGStudio MAX are compared to results from Volume Player (developed by Fraunhofer EZRT) and iAnalysis (developed by University of Upper Austria). The “threshold” method was applied for all the three software tools with a threshold value obtained by the “ISO50” technique described in Section 3.3. The chart in Fig. 9 shows that deviations from nominal values are lower for VGStudio MAX than for the other two software tools, while Volume Player and iAnalysis generate exactly the same results. The reason why both the latter software tools demonstrate the same behaviour is the fact that they use the same calculation procedure. In a first step, the data is binarized according to the threshold value; i.e. “0” is attributed to the material grey values and “1” is attributed to internal defects (background grey values). In a second step, Connected Component Filter (CCF) is applied for the separation of pores and their labelling [30].

Nonetheless, fixed threshold value does not take into account variation in the contrast between material and background throughout the data set and can introduce additional errors to measurement results. Hence, application of a local-adaptive segmentation algorithm as discussed in recent publications [2,4,6] has potential to improve the measurement results.

4. Conclusions

In this work, the reference object with artificial internal defects introduced in the previous publication [21] was redesigned, improved and applied for thorough evaluation of CT internal porosity measurement errors. Several investigations were performed in order to determine the influence of CT parameters settings on measurement errors, the repeatability of measurements and the effect of different approaches to volume measurements. In addition, results from real CT scans were validated by simulations and three different evaluation software tools for CT data processing were compared.

The study on the influence of voltage and current on porosity measurement errors has proven that these factors are important, particularly for small defects. The variation caused by voltage and current is below 4 μm in the case of diameter and depth measurements and below 3% in case of volume measurements. The relationship between tube voltage and current, and deviations in measurements has been determined as follows: the higher the values of tube voltage and current, the lower the observed deviations from reference values. The two main reasons for the improvement in measurements with higher tube voltage and current are: (i) the image noise is approximately inversely proportional to the square root of the tube current, i.e. the image noise decreases with increasing the tube current; (ii) the generation of X-rays increases with the square of the tube voltage, i.e. by increasing voltage, lower noise and better contrast can be achieved in the acquired projections. Nevertheless, it must be noted that, by increasing voltage and current, the tube power increases as well. An increase in tube power can affect the focal spot size, producing a deterioration of the resolution and other image parameters. In this study, the tube power was kept below 8 W, ensuring that the focal spot size was kept at a minimum (3 μm). As a consequence, the effects of tube voltage and current were isolated.

Based on the observed trends, to obtain the best results in evaluation of internal defects by CT, use of high settings of U and I is
Fig. 8. Simulation results: a) influence of CT parameters settings on $D$ measurements, b) influence of CT parameters settings on $Z$ measurements, c) influence of CT parameters settings on $V$ measurements, d) relative mean deviations of $V$ measurements related to current and voltage settings.
suggested. Nonetheless, one has to take into account also other boundary conditions such as expected structural resolution, scanning time, etc.

The measurement repeatability was evaluated based on results of 12 different scans, repeated under the same “optimal” conditions. Mean deviations and standard deviations were calculated for the results of the 12 scans. The outputs of this study show that the mean error of diameter and depth measurements can be below 5 μm with standard deviation ranging from 11 μm for the smallest defects to less than 1 μm for the largest ones. As for volume measurements, the relative mean deviation is below 10% for defects below 200 μm in diameter, while it is below 5% for defects larger than 200 μm in diameter, with standard deviations up to 6% in the case of smaller defects.

Two techniques to calculate the volume of defects were compared in this publication: (i) calculation based on measurements of fitted elements and (ii) Defect analysis module embedded in evaluation software VGStudio MAX. Results have shown that the former technique is suitable for larger defects, while the Defect analysis module has shown stable performance over the whole defects range.

In order to validate the results from real CT scans, simulations with extended range of volume and current were performed. Comparing the results of simulations with those of the real CT scans, it was seen that the trends observed on both data sets have the same tendencies. Yet, the magnitude of deviations is lower in case of simulations because they omit some influencing factors, such as geometrical instability of the system and focal spot drift.

Performance of three different CT evaluation software tools - namely VGStudio MAX, Volume Player and iAnalyze – in determining the volume of internal defects was compared. The outcomes demonstrate that the lowest measurement errors are given by VGStudio MAX. The latter two software tools achieve same results, as expected, because their calculation method is identical.

Results of all performed analyses show that measurements of smaller defects are more problematic, as the errors and standard deviations are constantly higher than for larger defects. Furthermore, the CT measured volume of all 72 defects appears to be higher than reference values. This effect is caused by averaging, lower sharpness of CT data and decrease of information content with decreasing magnification.

The investigation presented in this paper gives a comprehensive overview of CT performance in the evaluation of internal defects and confirms the high potential of CT in this field.

Acknowledgements

This work has received funding from the European Union’s Seventh Framework Programme under grant agreement No. 607817, INTERAQCt project.

The authors also would like to thank Mr. Christoph Heinzl (University of Upper Austria) for providing iAnalyze software tool, Mr. Stefan Kasperl (Fraunhofer EZRT, Germany) for providing Volume Player software, and Mr. Michael Neugebauer (PTB, Germany) for μ-CMM measurements.

References


