Methods to ensure accuracy and reliability of analyses and measurements done on CT data-sets

Stefan RIETH-HOERST¹, Christof REINHART¹, Thomas GÜNTHER¹, Tobias DIERIG¹
Johannes FIERES¹

¹Volume Graphics GmbH, Wieblinger Weg 92a, 69123 Heidelberg, Germany
e-mail: rieth-hoerst@volumegraphics.com, reinhart@volumegraphics.com, guenther@volumegraphics.com, dierig@volumegraphics.com

Abstract

Within the last years computed tomography (CT) has developed into a more and more powerful method not only for the inspection of defects in a broad variety of technical parts but also for metrology applications and as a tool for the exact analysis of internal structures. Typical application ranges are dimensioning, nominal-actual comparison with CAD data, wall thickness analysis, porosity and inclusion analysis, as well as determination of fiber distribution and orientation in fiber enforced materials. In order to use the full capacity of CT, it is important to have a reliable software tool to perform such analyses on the measured CT data sets. Of course it must be ensured that these analyses deliver repeatable, precise and thus trustable results. Volume Graphics puts a lot of effort into ensuring this for its software package VGStudio Max. This is why a lot of investigations and studies on this topic have been performed internally as well as together with independent partners like industrial customers or scientific institutes. One of the more common investigations that have already been performed regularly and with the desired results was the direct comparison of a CT analysis with measurements performed with other methods traditionally used in the field of metrology. The result there were so overwhelmingly in favour of CT that using CT for metrology meanwhile is commonly accepted to be state-of-the-art. Another way of ensuring the accuracy of algorithms and analyses is the usage of synthetic as well as simulated CT data. Results using this approach for the analysis of fiber orientation determination projects together with the companies Bosch and BASF will be presented. Moreover, this paper will also present examples that show a comparison of these data with results from measurements on real specimen. In cases where a defect analysis as well as a measurements of porosity has been performed a comparison of the determined results with ‘the reality’ is also very feasible and easily performed. Well known integral values for porosity can be achieved by the proper fabrication of a test specimen with a predetermined known volume, density and weight. Moreover the dimension of voids and shrinkage can be compared directly between reality and CT by producing properly polished sections by using a classical standardized destructive testing method. Investigations performed, e.g., by VW led to results that an analysis based directly on the CT measurements according to VDG specification P 201, P 202 can be performed virtually as well and will be accepted by VW. We will present related investigations that show the capability of gaining exact measurement results out of CT investigations beyond the creation of 3D visualizations.

Keywords: measurements, accuracy, metrology, defect analysis, fiber orientation
1. Today’s Industrial CT Applications

Industrial X-Ray CT is not only used in central quality labs any more, it is moving more and more directly into production. CT now is commonly accepted as a valid inspection method for industrial use. This becomes apparent by the increasing number of user and the rising amount of verifications that proof the accuracy and reliability of this inspection method. X-ray scanning virtualizes the complete test specimen, sometimes in sub micrometer voxel sizes, and aside from offering a complete 3D virtualization of the part a high diversity of applications can be derived.

For the Inside View and Segmentation, manual, semiautomatic or – using the component structure of a CAD model – full automatic segmentation helps to better identify and separate components very fast which finally allows to measure properties and judge the overall quality of a part. Coordinate measurement on CT data allows for inspection tasks to be performed which cannot efficiently be accomplished – if at all – when using conventional destructive or other non-destructive testing methods, e.g. for measuring „hidden” structures. Nominal/Actual Comparisons directly compare the dimensions of a part between CAD and Voxel Data or between two voxel data sets. Insufficient or excessive wall thicknesses can be automatically localized within the CT-Data. Destructive methods like grinding patterns can be replaced by analyzing material discontinuities like pores, holes and inclusion, e.g. in castings and plastic parts. CT scans of Fiber Composite Materials finally can be used to analyze the individual fibers, their orientations, concentration and length distribution. This allows the direct comparison between the real world and the virtual world, e.g. for injection molding simulations or mechanical simulations. Porous materials can be characterized according to cell size, surface area, edge direction and thickness distribution of the cells of foam structures or filters materials. CT data is moreover being used to determine physical material properties by numerical simulations. Transport phenomena like permeability can be calculated directly on voxel basis. Numerous examinations have been performed for evaluating accuracy and reliability of industrial x-ray CT.

2. Examples to Determine Reliability and Accuracy

The examples shown below are always on basis of the given voxel size of the respective CT-System. The focus is on the accuracy and reliability of the applications done on CT data-sets. Industrial companies like Bosch, BASF and Volkswagen, drive such verifications to qualify the inspection methods for further use in their product development process.

2.1 Comparison to other measurement methods

2.1.1 Subvoxel precise separation of materials and surfaces

For nearly all kinds of CT analyses the precise surface determination, thus the differentiation between material and surrounding air, is essential. The CT scanner delivers a certain size for a voxel, including a grey value per voxel. A local adaptive surface determination, using the partial volume effect, allows a subvoxel precise surface determination. Please refer to Figure 1.
In order to compare the results of coordinate measurement between CT Scans and opto-tactile measurements, six fuel injector nozzle boreholes were compared in five measurement positions (Figure 2).

In this example, the comparison of both methods showed a measurement uncertainty of ≤ 1 µm (Figure 3). Today, the local adaptive surface determination is an accepted standard. As a simple rule of thumb: with good image quality CT data it is possible to reach about 1/10 of a voxel in measurement uncertainty.
2.2.2 Analysis of scanned fiber composite material and comparison with 2D analysis methods

Fiber composite materials such as CFRP or GRP are playing a major role in modern product design. CT data is able to show detailed information of the internal structure of a part. For validation of these results, a sample was scanned by a CT system and the results were compared with analyses obtained with those from established 2D methods.

![Image of Fiber orientation analysis result](image1)

Figure 4 Fiber orientation analysis result of a sample with a 30% filling ratio

The sample has a thickness of 3 mm and was scanned with a resolution of 3.5 μm. The color coded overlay on the left side shows the orientation deviation from the z-axis. The results of the software based fiber orientation analysis in comparison to a 2D measurement is shown on the right side.

Figure 4 shows a good agreement between the results of the two validation methods. Thus CT delivers reliable and valuable information about the characteristics of composite materials, e.g. their mechanical properties which are based on the fiber orientation.

2.2.3 Comparison of accuracy between voxel based data and common STL data

CT now is also a common tool for coordinate measurement. Metrology applications very much depend on the measurement strategy applied like defining appropriate coordinate systems and reference objects. The data basis should always be the original data source available from the CT scanner. There are two general approaches: measuring on the basis of voxel data and measuring on a polygonal representation, which shows differences in terms of measurement uncertainty as well as performance of the total coordinate measurement process.

![Image of Surface voxel based vs. meshing](image2)

Figure 5 shows the extracted STL mesh (yellow line) compared to the original voxel data surface (white line) in high magnification. It shows that the STL mesh does not represent the original surface in the most optimum way.

<table>
<thead>
<tr>
<th>STL Data Extraction Mode</th>
<th>Voxel size/ sampling distance</th>
<th># Triangles</th>
<th>Time needed for STL extraction</th>
<th>Data set size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.5</td>
<td>~2.2 million</td>
<td>1:45 min</td>
<td>109 MB</td>
</tr>
<tr>
<td>Oversampled</td>
<td>2</td>
<td>~29 million</td>
<td>&gt;25 min</td>
<td>1.4 GB</td>
</tr>
<tr>
<td>Voxel Data Surface</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>170 MB</td>
</tr>
</tbody>
</table>

For achieving a good approximation on the original voxel data, the mesh generation can be extremely oversampled. However this results in larger file sizes and increased computing times (Figure 6). Figure 6 Table overview meshing
A data set (Figure 7) was used to determine the level of measurement uncertainty that will be added by converting voxel data into polygonal data. The deviations between the original voxel data surface and the STL surface representation extracted in “precise mode” was compared by applying the same measurement template onto both models (voxel size of the CT scan 39 µm).

For 20% of the measured features the conversion from voxel data into STL resulted in a measurement deviation of 1/10 of a voxel or more. Some deviations added a measurement uncertainty of > 5% compared to the voxel data.

2.2.4 Impact of different CT Systems onto Measurement Accuracy

Depending on the required resolution for defect detection, the CT systems used can play an important role. This is an example from a part which has been scanned on the premises of a supplier and – once again – on the CT system of a customer.

CT manufacturer A, voxel size 42 µm
Single defects are not identifiable

CT manufacturer B, voxel size 29 µm
Single defects are still identifiable

The criteria of maximum pore sizes is exceeded using the system of manufacturer A, whereas B says the maximum pore sizes are acceptable.

2.3 Algorithm and analyses verified on analyzing simulated CT data, where the results are exactly known mathematically

2.3.1 Tensor analysis on simulated fiber composite materials
For validation of a fiber orientation analysis, a virtual CT data set with exactly known fiber distribution and orientation was created and validated by the software VGStudio MAX.
Fiber orientation analysis results for a data set with a filling ratio of 17 vol% (top) and for a data set with a filling ratio of 6 vol% (bottom). On the left the evaluated slices are displayed. Only a small stripe over the thickness was evaluated with a grid of 6 columns (see color coded overlay). The results of the software based fiber orientation analysis in comparison to the calculated true values are shown on the right side. (Resolution for both simulated data sets: 2 μm) It could be thus shown, that the CT analysis produced a high conformity to the simulated data.

2.3.2 Transport Phenomena based on artificial structure analysis. Mathematically determined flow rates compared to simulations on voxel data

The physical characteristics of porous structures like stones and foams are relevant for different applications, like the exploration studies done in the oil and gas industry. Today’s CT systems are able to scan such materials in high resolution so that their characteristics can be simulated directly on basis of the voxel data sets. Of interest is the question of the relation between the size of the porous structures and the voxel size, respectively the simulation grid size, to perform reasonable analyses, e.g. for calculating transport phenomena. Thus artificial and mathematically computable tube structures were created and the software has been used to analyze the flow rates (Figure 10).
For determining the relation between the size of the porous structures and the necessary size of the simulation grid, the diameter of the tubes was varied, whereas the size of the simulation grid was kept constant (Figure 11). The results of the simulated flow rates were compared to the mathematically determined numbers (Figure 12).

Figure 11 shows the simulated and the calculated flow rates (on the y-axis), depending on the diameter of the tube (x-axis). The conformity between the simulation and the calculation of the flow rates is very good for diameters > 3 grid cells.

In order to perform reliable permeability simulations based on CT scans, this implies that relevant porous structures should be resolved by at least four simulation grid cells. In cases the CT scan resolution fulfills this requirement, the voxel data set can be directly used as simulation grid. In cases of a lower scan resolution, a more narrowly defined simulation grid of at least 4 cells have to be laid in-between the subvoxel precise determined surfaces.

2.4 Verification, if CT analysis fits to industry-known standards

2.4.1 Porosity Analysis CT Data versus Grinding Patterns

The evaluation of CT data allows an automated detection and analysis of internal defects, porosity or inclusions, e.g. in castings. Volkswagen has developed a standardized method for evaluating porosity under VDG specification P201 and P202. Initially, the specification has been based on grinding patterns. Today, CT is an approved and accepted method for complying with the above mentioned VDG standards thus allowing for the inspection to be done virtually.
4. Outlook

Once a part is scanned by an industrial X-Ray CT it becomes virtual and allows a variety of different analyses. The evaluations can be done by different specialist departments, independently from where they are located. Product development and design have already become virtual, thanks to the developments of CAD. Using industrial CT, product optimization, quality control and failure analysis are becoming more and more virtual in future. Stakeholders within industry and organizations are accompanying this process in order to verify accuracy and reliability.

Product development and design are already virtual

Product optimization, quality control, failure analysis are becoming virtual as well

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