Uncertainty Evaluation of Pore Analysis for Additively Manufactured Parts using Cross Sections

Leonard Schild, Manuel Fülling, Benjamin Häfner, Gisela Lanza
1 wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, e-mail: Leonard.Schild@kit.edu

Abstract

Additively manufactured (AM) workpieces, which have been produced by means of laser beam melting (LBM), tend to show quality relevant pores and cracks on the inside. Quality assurance on these parts may be conducted using x-ray Computed Tomography (CT), as CT is able to spot pores and cracks in the entire volume of a specimen. However, the uncertainty of detection of such cavities in a CT measurement is unknown. To tackle this shortcoming, different authors have compared metallographic cross sections to CT images. None of these investigations have compared the cross section’s plane directly to the corresponding plane of the CT’s 3D voxel image, without using features of the CT image itself, though. This paper introduces a special artifact as reference standard, whose pyramid like form allows a direct comparison of a metallographic cross section and the corresponding plane in a CT scan. The shape of the test object allows to calculate the parameters of the plane equation of the metallographic cross section in a coordinate system fixed to the test object. The plane equation is used to identify and investigate the corresponding plane in the CT scan. By comparing this artificial cross section from the CT scan with the cross section from the metallography specimen, the CT’s performance for detecting pores is assessed. As a result, a general method to test any CT’s capability to detect pores in an AM part is given by using cross sections of test objects with the proposed pyramid like form.

Keywords: Additive Manufacturing, Measurement Uncertainty, Metrology, Reference Object, Cross Section

1 State of the art in uncertainty evaluation of pore detection

CT is a promising measurement technology to characterize specimen, which are manufactured by means of additive manufacturing such as laser beam melting. CT allows to conduct dimensional measurements and pore detection during the same measurement. Both tasks are of high relevance to AM parts [1]. Despite this great advantage in comparison to other measurement technologies, CT lacks traceability for pore detection. While many publications have described approaches to determine the uncertainty of CT for dimensional measurements, only a few publications have dealt with the topic of uncertainty evaluation of pore detection. Most commonly the measurement uncertainty in dimensional measurements is derived from reference measurements using calibrated artifacts according to VDI 2630 2.1 [2]. This approach is difficult to transfer to pore detection, as no suitable reference technology is present. A common technique to characterize pores is to analyze micrographs of cross sections, though. Tammas-Williams et al. analyze cross sections which are obtained from workpieces that have been scanned by CT beforehand [3]. It is concluded that pore size distribution of cross sections and CT are comparable. The results are not obtained by direct comparison of CT data and corresponding micrographs of cross sections, though. Only a statistical analysis is used to show similarity. Wits et al. compare a micrograph of a cross section to a CT scan by using a best fit algorithm [4]. They find that cross sections and CT yield similar results but no detailed explanation is provided. Another possibility to estimate the uncertainty of pore measurements is to use a calibrated reference object. Hermanek et al. present a reference object that has been produced by means of micro milling and calibrated by tactile and optical CMM [5]. They conclude that the uncertainty of pore measurements depends on the usage of correct settings of the CT and the processing software. However, it is unclear how well the half cubes used on the reference object represent real pores in additively manufactured work pieces. Kiefel et al. use a special reference object which contains pores of different sizes [6]. They state that CT is able to analyze pores half the size of the voxel size. In summary, there are no methods available to provide reference measurement of pores for the whole volume of a CT scan while dealing with pores that are shaped realistically, i.e. like the ones found in AM parts.

2 Method

In the following, a method is described which addresses these shortcomings. The approach allows to locate and map a plane in a CT scan. Using this technique, it is possible to directly compare results from computed tomography measurements with micrographs of cross sections. By providing micrographs of many cross sections of a work piece, it is possible to obtain a sound estimation of the pore distribution in the whole work piece. By accepting micrographs of cross-sections as a suitable reference method for measuring pore position and form, the uncertainty of a CT based pore analysis can be assessed using the presented method. The method is based on the idea that a plane may be characterized by at least 3 points in a cartesian coordinate system. If the plane parameters describing its position and orientation are given in a work piece’s local coordinate system, they can be used to identify this plane directly. Thus, if the plane parameters of a cross section are known in a local coordinate system of the work...
piece, it is possible to find this plane in a CT scan, as well. However, after preparing the cross section it is not possible to reach any other features of the work piece in order to register its local coordinate system because the work piece is embedded in resin. By using a work piece which is formed in such a manner that the shape of the cross section in the micrograph allows direct deduction of the cross section’s plane parameters, the work piece can be registered by analyzing the cross section alone. Such a work piece is shown in Figure 1. It has a pyramid-like shape. The blue rectangle in Figure 1 b) represents the part of the work piece, which would be visible in a micrograph of a cross section. If the slope and position of the pyramid’s sides are known, it is possible to derive the plane parameters by using the length of the rectangle’s sides as well as the enclosed angles.

![Reference object with coordinate system](image1)

**Figure 1. Schematic representation of reference object for comparison of CT scans and micrographs of cross sections**

![Technical drawings](image2)

**Figure 2. Technical drawings of reference object for comparison of CT scans and micrographs of cross sections**

Considering the idea stated above, the object shown in Figure 2 is designed. The work piece has four sides to strike a balance between being quick to measure using tactile CMM as well as allowing for precise results by providing more than the minimal amount of three points. A groove on one side allows to identify the rotational orientation. The threaded hole on the front allows for easy mounting on a tactile CMM. The procedure how this work piece is used is described in the following process containing 10 steps. The process applies for one plane of a virtual cross section and needs to be repeated for all planes that are supposed to be analyzed.

1. Print material
2. Shape material by means of milling
3. Measure all planes with tactile CMM
4. Conduct CT Scan
5. Generate micograph of cross section
6. Deduce edge points from micrograph
7. Calculate spatial position of points
8. Use points to define plane in CT scan
9. Apply pore detection algorithm
10. Compare results in identified plane
1. Print Material

An additive manufacturing machine, such as a laser beam melting machine, is used to print a block which is bigger in all dimensions than the reference work piece. The resulting work piece typically contains pores. The work piece shown in Figure 3 was created using a LBM machine SLM Solutions 280.

2. Shape Material by means of milling

After the material has been printed it is necessary to shape it. A milling machine is used to generate a work piece according to the technical drawing (compare Figure 2).

![Figure 3. 3D printed aluminium material](image1)

![Figure 4. Finished reference object made from 3d printed aluminium after milling](image2)

3. Measure all planes with tactile CMS

As shown in Figure 5 the work piece is measured with a tactile CMS. The threaded hole is used to provide easy mounting on the machine. As is visible in Figure 5 b) the local work piece coordinate systems is used to express the measured planes. In this publication a Zeiss O-INSPECT 322 CMM is used.

![a) Reference object on tactile CMM](image3)

![b) Planes measured on CMM](image4)

4. Conduct CT Scan

After the workpiece is measured on the CMM, a CT scan like the one in Figure 6 is conducted. It is useful to use different settings in order to make sure that good scan quality is achieved. For this publication a Zeiss METROTOM 800 CT device is used.

![Figure 6. CT Scan of reference object](image5)
5. Generate micrograph of cross section

In this step, a micrograph of a cross section is prepared. This is a complex process with many steps itself. The most essential three steps are the embedding, cutting and polishing. This means, the work piece is embedded in resin to prohibit the edges from braking away in the following cutting step. In a last step, the surface is polished. Using a microscope, many pictures of the surface of the polished cross section are made. They are stitched together using a special program, for example ImageJ. The microscope provides a scale on how to calculate millimeter from pixels in the stitched image, like the one in Figure 7.

6. Deduce edge points from micrograph

Using MATLAB, the micrograph is analyzed. Applying a segmentation algorithm using Otsu’s Method [7], the micrograph is binarized. Now, the edges of the segmented image are found by applying MATLAB’s Canny edge detector. This edge gives the outline of the rectangular shape of the cross section. Now, the edge points can be identified as those points that have the biggest distance to the centroid of the edge points. Using these edge points, the surrounding pixels of the sides are found. Straights are fitted through these pixels. Using the scale provided by the microscope, the length of the sides and their enclosed angles are obtained. The result of this procedure is shown in Figure 7.

7. Calculate spatial position of points

As a result of step 3, the parameters of the planes on the sides of the pyramid are known. By calculating their intersection, four straights are gained with parameters \((\mathbf{d}, \mathbf{n}, \lambda)_{1-4}\). In reference to Figure 1 it is known that the edge points \((\mathbf{p})_{1-4}\) from the previous step lie on these straights. Furthermore, the length of the vectors \((\mathbf{l})_{1-4}\) connecting the edge points as well as the angles \((\alpha)_{1-4}\) these vectors enclose are known from the previous step. The following set of 20 equations for 16 unknowns \((P(x, y, z), \lambda)_{1-4}\) can be deduced. It needs to be solved numerically because of nonlinearities, using e.g. MATLAB.

\[
\begin{align*}
\mathbf{p}_1 &= \mathbf{a}_1 + \mathbf{n}_1 \lambda_1 \quad \text{(1)-(3)} \\
|\mathbf{l}_1| &= |\mathbf{p}_1 - \mathbf{p}_4| \quad \text{(13)} \\
\mathbf{p}_2 &= \mathbf{a}_2 + \mathbf{n}_2 \lambda_2 \quad \text{(4)-(6)} \\
|\mathbf{l}_2| &= |\mathbf{p}_2 - \mathbf{p}_1| \quad \text{(14)} \\
\mathbf{p}_3 &= \mathbf{a}_3 + \mathbf{n}_3 \lambda_3 \quad \text{(7)-(9)} \\
|\mathbf{l}_3| &= |\mathbf{p}_3 - \mathbf{p}_2| \quad \text{(15)} \\
\mathbf{p}_4 &= \mathbf{a}_4 + \mathbf{n}_4 \lambda_4 \quad \text{(10)-(12)} \\
|\mathbf{l}_4| &= |\mathbf{p}_4 - \mathbf{p}_3| \quad \text{(16)} \\
\end{align*}
\]

\[
\begin{align*}
\alpha_1 &= \cos^{-1} \frac{\mathbf{l}_1 \cdot \mathbf{l}_4}{|\mathbf{l}_1| \cdot |\mathbf{l}_4|} \quad \text{(17)} \\
\alpha_2 &= \cos^{-1} \frac{\mathbf{l}_2 \cdot \mathbf{l}_1}{|\mathbf{l}_2| \cdot |\mathbf{l}_1|} \quad \text{(18)} \\
\alpha_3 &= \cos^{-1} \frac{\mathbf{l}_3 \cdot \mathbf{l}_2}{|\mathbf{l}_3| \cdot |\mathbf{l}_2|} \quad \text{(19)} \\
\alpha_4 &= \cos^{-1} \frac{\mathbf{l}_4 \cdot \mathbf{l}_3}{|\mathbf{l}_4| \cdot |\mathbf{l}_3|} \quad \text{(20)}
\end{align*}
\]
8. Use points to define plane in CT scan

After the set of equations is solved, the four points \( \vec{P}_i \) are known. Following registration of the work piece in the CT scan processing software, these points can be expressed in the local work piece coordinate system. Now, these points are used for fitting a plane to them. In this publication VG Studio Max 2.2 is used to process the CT scan.

9. Apply pore algorithm

After defining the plane, which allows to perform a virtual cross section, the CT scan is checked for pores. Different types of pore detection algorithms can be used in order to compare their results. At this point it is useful to place a region of interest around the plane. Doing so, only part of the reconstructed volume is analyzed in order to save time.

10. Compare results in identified plane

Now, the plane of the cross section is known in the CT scan and the virtual micrograph of the CT scan is compared to the micrograph from step 5. Figure 8 shows an exemplary result. In order to deduce an uncertainty in pore measurement, the size, position and form of every pore in the micrograph of the cross section as well as in the virtual micrograph needs to be measured and compared. The comparison should be undertaken automatically using comparable techniques of image processing to make them comparable. Using commercial software, this is not easily possible. Pore detection algorithms like VG studio’s DefX, which is used in this paper, either work on the whole volume of the CT scan or they are limited in the amount of information they provide on pore position and shape. As CT scans are three dimensional and micrographs of cross sections only contain two dimensional information, perfect comparability in the sense of ISO 15530 [8] will never be present. However, using evaluation methods that are more comparable, a better estimation of the uncertainty in pore measurement could be achieved.

![Figure 8. Comparison of a micrograph of a cross section and a virtual micrograph obtained from a CT scan of the same object in the same plane. Pores in the virtual micrograph are marked red](image)

3 Results

The method was tested for one sample geometry with two scan settings. The results are shown in Figure 9. Both CT scans were made with a Zeiss METROTOM 800. While the first scan was made using a copper prefilter the second one was made using an aluminum prefilter. By using only an aluminum filter, the diameter of the focal spot is reduced from 40 to 20 \( \mu \text{m} \). The complete list of settings is shown in Table 1. The virtual micrograph is made by using VG Studio MAX 2.2 and the DefX algorithm. The surface is determined by using the automatic function of VG Studio.

The analysis in the following is performed in a qualitative manner to gain first results. These are used for an interpretation and a discussion. Looking at the virtual micrographs in Figure 9 it is clear that the first scan is of better quality. Artifacts are visible in the second scan in the orientation groove. Additionally, the work pieces edges appear to be curved in the second scan. However, the pore distribution does not look very different compared to the real micrograph and the first virtual micrograph. Both virtual micrographs resemble the physical micrograph pretty well in most areas. Only the big pore in the middle of the virtual micrograph is not visible in the physical micrograph.

<table>
<thead>
<tr>
<th>Table 1. CT Settings used</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT Scan</td>
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<tr>
<td>2</td>
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</table>
This leads to the question how precisely the plane of the cross section is found with the presented method. To answer this question, two further virtual micrographs are analyzed. They are shown in Figure 10. Both planes are parallel to the plane of the first virtual cross section. The first one is shifted 40 $\mu$m in positive z direction while the second one is shifted 40 $\mu$m in negative z direction. In the second virtual micrograph (-40 $\mu$m), the pore in the middle is smaller and the distribution of the pores in the lower right corner looks better, too. This indicates that the process of performing a virtual cross section leads to a discrepancy of 40 $\mu$m between the virtual and the real cross section.

To prove that the discrepancy between the physical cross section’s plane and the virtual plane is 40 $\mu$m, the work piece is freed from the surrounding resin. Now, the parameters of the plane of the cross section are obtained by using a tactile CMM. The work piece is registered as of step 5 of the process described above. Then, the plane of the cross section is measured. Calculating the intersection of the plane and the four straights used in step 7 of the process, four points are obtained. They are given in Table 2. The results show, that the virtual cross section is indeed shifted by circa 40 $\mu$m. This is a good result for a first try as the thickness of layers of LBM machines is of roughly the same magnitude. However, this is more than the smallest pores that are detected. Therefore the process needs to be optimized. To do so, the true plane parameters need to be known. Obtaining them by freeing the work piece from the resin is highly impractically. Two prototypes were damaged during this process. Without a validation like this the process cannot be optimized, though. Therefore, an optimized design of the work piece is presented in the next section.

<table>
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<tr>
<th>Point</th>
<th>Virtual x</th>
<th>Virtual y</th>
<th>Virtual z</th>
<th>CMM x</th>
<th>CMM y</th>
<th>CMM z</th>
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</tr>
</tbody>
</table>
4 Outlook

A new test object is shown in Figure 11. It resembles the first object but has two cylindrical features on the backside that are used for registration during tactile measurement. These are covered by a lid while placing the object in resin. Even if the lid is damaged during removal of the resin, the registration features are not damaged. This is demonstrated in Figure 12 on a prototype, which is made of conventional and not additively manufactured aluminum. Looking at Figure 12, it is clear that the registration features are not deformed during the removal.

In future, this geometry will be used for further experiments. In a first step, the process shown above will be improved using the insight gained using the new work piece. Afterwards, a software solution for pore detection will be implemented which allows for better comparability between micrographs of cross sections and virtual cross sections.

![Figure 11. Improved work piece with registration features on back side that is protected by a lid during embedment](image)

![a) Lid in place b) Lid removed](image)

**Figure 12. Prototype of new test object with lid and resin removed**

5 Summary

In this paper, a novel method is presented to compare micrographs of cross sections to so called virtual micrographs from CT scans. The method uses a work piece whose shape is determined by using a tactile CMM. Afterwards, the work piece is used to create a micrograph of a cross section, which is used to perform pore analysis. Using the appearance of the work piece in the micrograph of the cross section, the plane parameters of the cross section in a local coordinate system of the work piece are obtained. The plane parameters are used to find the plane in a CT scan of the same test object. Now, the detected pores in the virtual micrograph of the cross section of the CT scan are compared to the physical micrograph.

First experiments show that the method enables to detect planes with an accuracy of up to $40\,\mu m$. While this is good enough for bigger pores, further improvements to the method must be made in order to perform a comparison of smaller pores. To do so, an improved design of the used work piece is proposed. Using this new design, further experiments need to be conducted. These should use pore detection algorithms that are better comparable to those used on physical micrographs of cross sections. After enhancing these two shortcomings, the method may be used to estimate the uncertainty of CT in pore detection.

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References


