

A NEW TEST PIECE FOR GEOMETRY AND DEFECT MEASUREMENTS WITH MICRO-CT

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Abstract

We present a modified aluminium casting, which is especially suited as test piece for measuring the geometry and casting-defects with cone-beam micro-focus X-ray systems, and which may become a reference standard for dimensional measurements and defect detection.

The accuracy of dimensional measurements of outer surfaces with CT can be determined by comparison with tactile measurements. But CT is the only non-destructive method to measure inner surfaces which are inaccessible with tactile or optical methods.

To get a test piece with inner geometries measured by tactile means, we divided a small (roughly 12 cm x 9 cm x 6 cm) aluminium cylinder-head (casted by the company ACTech in Freiberg, Germany) into four pieces in such a way that most inner surfaces can be reached with a tactile probe. Reference geometries (spheres and cylinders) were applied to define a coordinate system for aligning the measurements in the disassembled and re-assembled state (see Fig. 1). The four pieces were re-assembled after the tactile measurement (see Fig. 2).

The test piece also contains casting defects. For being able to use the assembled cylinder-head also as reference sample for defect detection, measurements with higher spatial resolution and better signal-to-noise ratio were performed on the single parts. For improving the reliability of the reference measurements, CT-measurements of each part were carried out in three different orientations, and the individual defect detections were reconciled to obtain a reference data-set with a high probability of defect detection and a low rate of erroneous detections.

We discuss the results of measurements in the assembled state with respect to the reference data for both, dimensional measurement and flaw detection.

1. Introduction

Computed tomography (CT) is an established method for quality control in industrial production, e.g. in the automotive industry [1]. A method for getting quantitative information on its ability to measure the geometry and to detect defects is to measure calibrated test pieces (reference standards).

Our aim was to create a test piece with similar properties as actual casting pieces, e.g. similar material (aluminium) and inner free-form surfaces. As an industry-near test piece we chose an aluminium single-cylinder head with the dimension 12 cm x 9 cm x 6 cm, casted by the company ACTech in Freiberg/Saxony, Germany, the “Mini-Cylinder-Head No. 5” (Fig. 1).

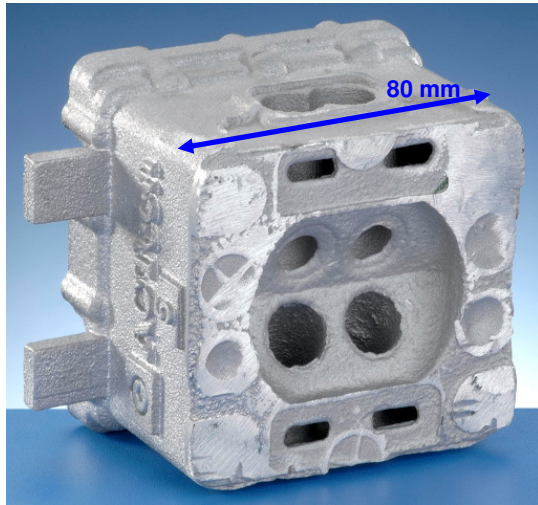


Figure 1: Mini-Cylinder-Head No. 5 before processing

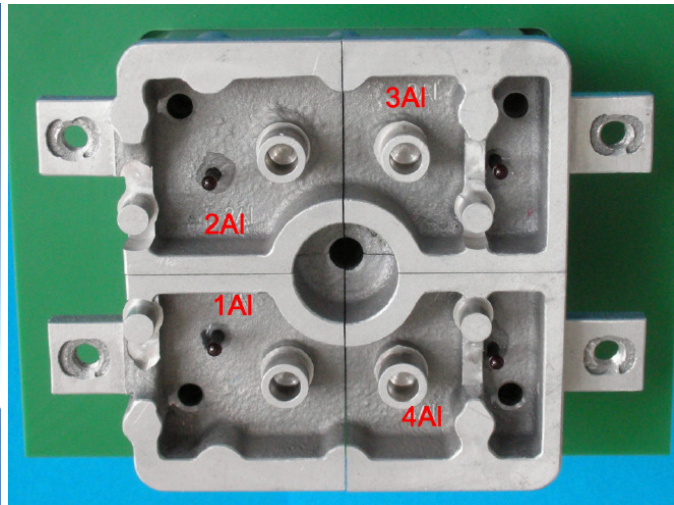


Figure 2: Mini-Cylinder-Head No. 5, divided into four segments

This casting piece contains inner surfaces and casting defects. To be able to calibrate the inner surfaces by tactile probing, the cylinder head was cut into four segments by electrical discharge machining in such a way, that large parts of the surfaces are accessible by a tactile probe (Figures 2 and 3). Reference geometries (3 spheres and 3 cylinders) were applied onto each segment. The positions and dimensions of the reference structures were determined with a coordinate-measuring machine (CMM). They define a work-piece coordinate system enabling the alignment of single measurements. The distances between the spheres of each segment (Figure 4) can be used to correct potential scale discrepancies between individual measurements.

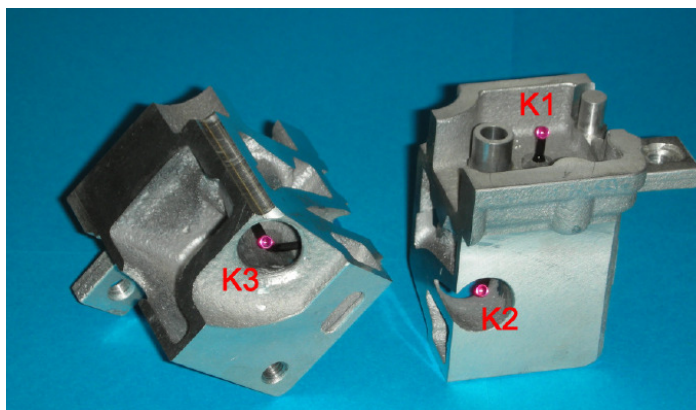


Figure 2: Two segments of Mini-Cylinder-Head No. 5

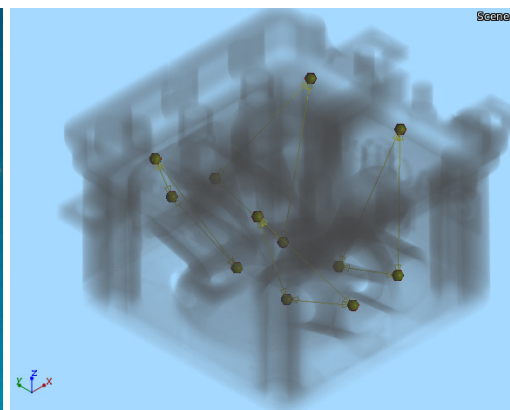


Figure 2: Positions and distances of the spheres

The thus prepared work-piece can now be used as test-piece for dimensional measurements and for defect analysis with CT.

2. Mini-Cylinder-Head No. 5 as test-specimen for defect detection

A test piece for defect detection must have a known defect distribution. For this purpose we performed measurements on the BAM-225kV-CT-device (with 210 kV acceleration voltage, and 0.75 mm of silver and 0.5 mm of copper as X-ray-tube pre-filters, in this order between tube and object) of the four single segments of the cylinder-head in three different orientations each (multi-orientation measurement, the “reference measurement”) with a higher resolution ($(48.0 \mu\text{m})^3$ voxel size) and a more “industry-like” measurement of the assembled cylinder-head ($(69.8 \mu\text{m})^3$ voxel size) with otherwise identical settings. The multi-orientation measurement allows to reduce orientation-dependent artefacts in the reconstructed volumes (edge artefacts, ring artefacts, beam hardening) by averaging data sets with different alignments of these. By averaging the data, the signal-to-noise ratio is also enhanced.

In [2] we already described a method to combine defect detections in the individual data sets within the voxel-data visualisation and analysis software VGStudio Max 2.0 (Volume Graphics GmbH, Heidelberg, Germany). There the defects in the individual measurements of the cylinder-head segments were searched with an adaptive threshold algorithm and converted to regions of interest (ROIs). After aligning the data sets via the positions and distances of the reference spheres, the intersection of these ROIs was calculated, which became the defect reference.

For the data set of the assembled cylinder-head the defect detection was performed also via adaptive threshold and conversion to ROIs.

The comparison of the ROIs provided information on the size distribution of the detected defects, but it was not possible to make statements on whether individual defects were detected in the merged measurement, which detections were erroneous detections, or how the detected size of the defects varied.

In this paper we present a different approach which allows analysing the detection of individual defects. This is shown exemplarily in a section of segment 1.

The three different orientations of segment 1 for the reference measurements are shown in Figure 5.

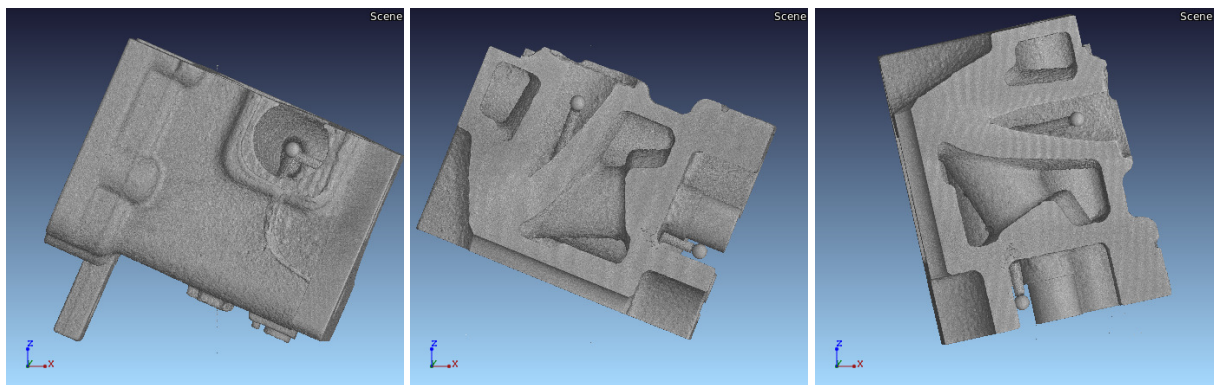


Figure 5: Orientations of segment 1 in the three individual measurements. The axis of rotation during the CT-measurement is in z-direction and in the image centre.

The three reference measurements and the assembled-state measurement were reconstructed in their original orientation but with the smaller voxel size of the reference measurement. With VGStudio Max the orientations of the reference measurements relative to that of the assembled

state were determined using the reference spheres. The rotation angles along the different axes and the respective offsets were used as input parameters for the reconstruction of the reference measurements, so that all data-sets to be compared were finally reconstructed in the same voxel grid.

To make use of the multi-orientation measurement, the three reference measurements were averaged, resulting in a higher signal-to-noise ratio and a reduction of artefacts (Figure 6).

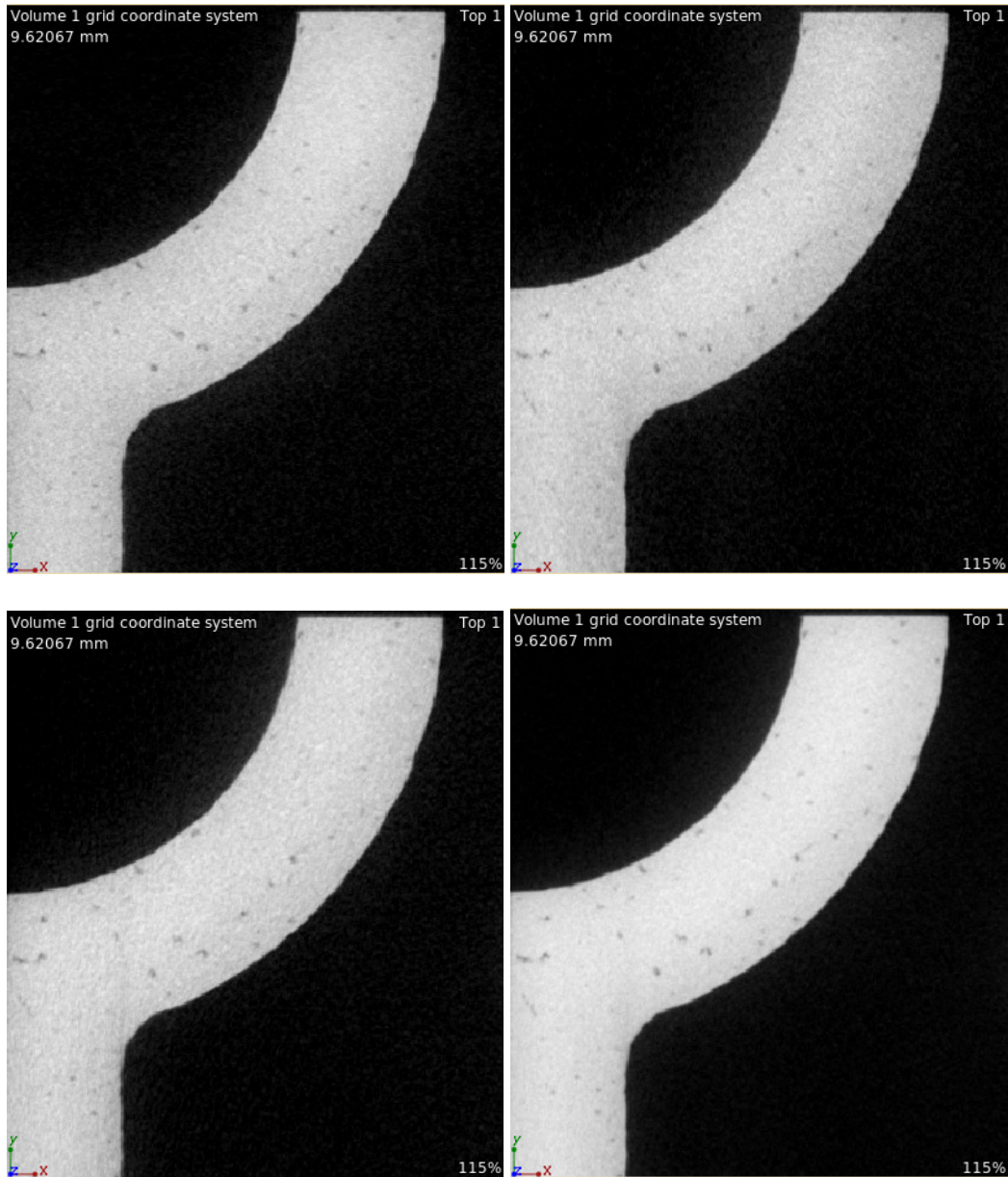


Figure 6: Slices through the aligned reference data sets (top and bottom left) and the averaged data set (bottom right). The signal-to-noise ratio in the averaged data-set is significantly enhanced and artefacts are reduced.

All grey-values in both volumes (the averaged one and the assembled-state one) were increased by one to have no values equal zero in the data. This is necessary for an unambiguous distinction between voxels belonging to a defect and ROIs in the later processing with ImageJ.

In the same sections of the data sets the defect detection with VGStudio Max was now performed (adaptive threshold, manually defined grey values, minimum defect size 27 voxels). The distribution of the detected defects in the averaged reference data and in the assembled-state data is shown in Figure 7.

To be able to analyse the detection of individual defects, those found were converted to ROIs. The voxel data of these ROIs were extracted, leading to voxel data-sets with zeros everywhere except in the ROIs, where the original values (larger than zero) are preserved.

The data with the extracted ROIs were now loaded into the open-source image manipulation program ImageJ (version Fiji 2009-04-29, <http://pacific.mpi-cbg.de/>). Using the ImageJ-plugin “Object counter 3D” (version 1.5.1, <http://rsb.info.nih.gov/ij/plugins/track/objects.html>) all connected regions with grey values larger than zero (where the ROIs had been) were determined. Results are data arrays where every voxel of each connected region is filled with its indexing number (“index data”) and tables containing information on each defect’s size and position.

In the considered section of the averaged reference data 1787 defects were detected, while there are 246 in that of the assembled-state measurement (Figure 7).

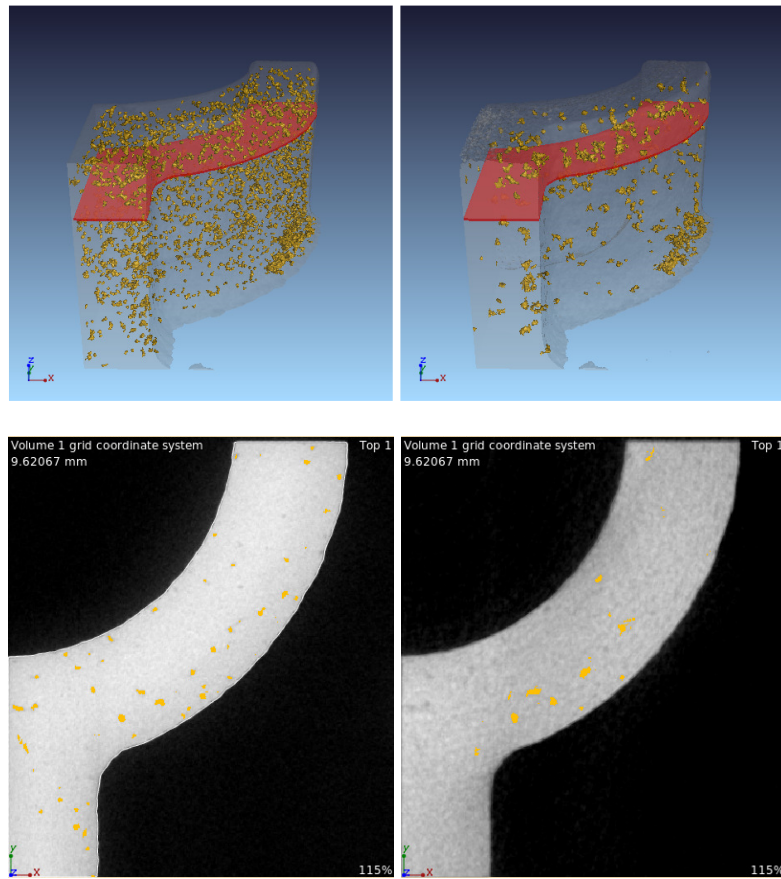


Figure 7: The detected defects (yellow) in the averaged reference data (left) and in the assembled cylinder-head measurement (right); *top*: the distribution in 3D view; *bottom*: a horizontal slice (the same in both, marked red in the 3D view)

To merge the information on the defects in both data sets, it is necessary to assign unique number ranges to the index data-sets of both analyses. This is done by multiplying one index data-set (in this case the one from the reference measurement) by a number large enough (e.g. 1000, which is

larger than the number of detected defects in the assembled-state measurement (246)), so that no overlap with the indices in the assembled-state measurement occurs. Then both index data-sets were added.

The resulting array now contains values smaller than 1000 where there is only a detection in the assembled-state measurement, multiples of 1000 where there was a detection solely in the reference data, and values larger than 1000 with the smaller digits deviating from 0 for detections in both data sets. Calculation of a histogram of the 3D-array with a bin-size of 1 now provides the information on the detection of each known defect, e.g. whether it was detected at all or detected as one or more separate defects. Combining this information with those stored in the tables created by “Object counter 3D”, the positions of the defects, the size of the overlap, and the summed size of the overlapping defects can be retrieved.

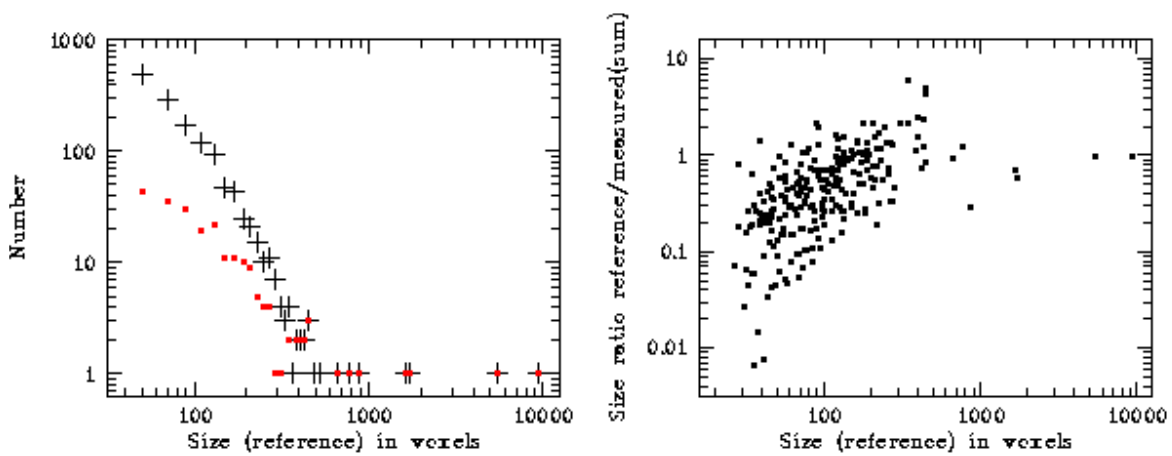


Figure 8: *left:* The number of re-detected defects in the assembled-state measurement depending on their size (red squares) compared to those in the reference measurement (black crosses). The bin-size for the histogram is 20 voxels. *right:* The ratio of the size of each defect in the reference measurement to the summed size of all overlapping defects in the assembled-state measurement.

Results of this individual analysis are shown in Figure 8. In the left panel it can be seen that only few small defects are re-detected, while all defects larger than 600 voxels are found. The right panel shows the ratio of the measured size of each defect in the reference measurement to the summed size of all defects in the assembled-state measurement, which are partially or completely overlapping the defect in the reference measurement. Ratios much smaller than 1 denote a much larger defect (or multiple overlapping defects) in the assembled-state measurement at the position where there is only (a small) one in the reference measurement. These are obviously erroneous detections and occur predominantly below a size of 100 voxels. Size ratios larger than 1 occur when not all parts of a defect are re-detected in the assembled-state measurement, e.g. because of the reduced signal-to-noise ratio or the reduced spatial resolution. Large defects have nearly the same size in both measurements (a size ratio near 1) and are thus detected reliably.

It is also of interest to get information on the properties and distribution of size and position of erroneous detections. For this purpose the process of adding the detected defects is modified such that the resulting array of the assembled-state measurement is multiplied by 10000 and the reference detections are added unmodified. Histogram analysis shows that erroneous detections have sizes below 300 voxels (Figure 9).

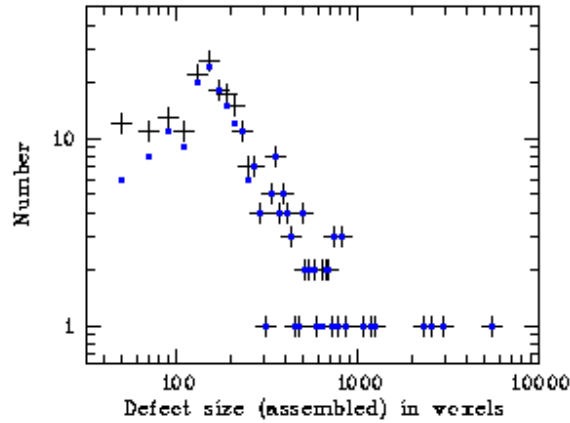


Figure 9: The number of all defects in the assembled-state measurement depending on their size (black crosses) compared to those detected in the reference measurement also (blue squares). The bin-size for the histogram is 20 voxels.

3. Mini-Cylinder-Head No. 5 as geometry test-specimen

The reference measurements of the individual segments were performed in three different orientations each. By aligning the data sets with the help of the reference spheres it is possible to study how measurements in different orientations effect the surface determination. A comparison with the data obtained at the assembled cylinder-head allows to quantify deviations resulting from the lower signal-to-noise ratio, the reduced spatial resolution, and beam-hardening effects.

To obtain a reference surface the aligned reconstructed volumes from the three measurements of segment 1 were averaged and a surface detection with an adaptive threshold was performed within VGStudio Max.

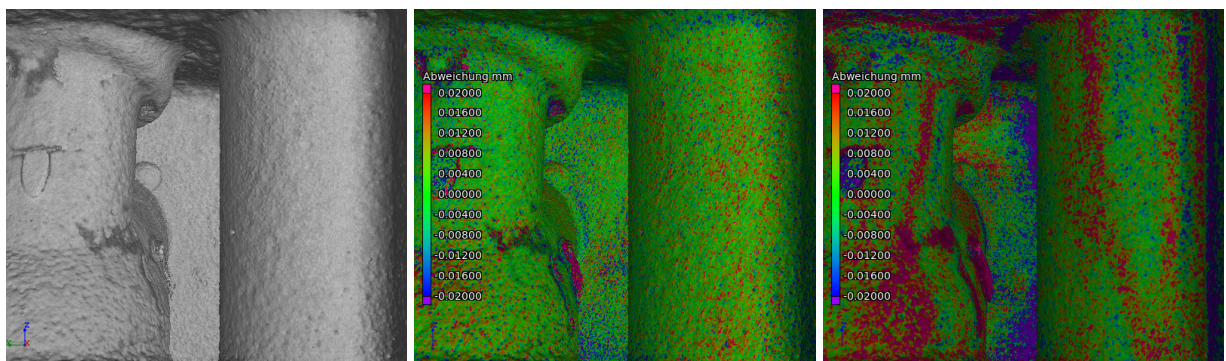


Figure 10: The surface of the averaged reference measurement (left), its colour-coded difference to one of the single measurements (the left one in Figure 5), and the difference to the assembled-state measurement

Figure 10 shows the comparison of the extracted surfaces on a detail of segment 1. In the left panel the surface obtained on the averaged reference measurement can be seen. The middle panel shows the colour-coded difference of the surface determined on a single reference measurement to that from the averaged data. The differences mainly arise from the lower signal-to-noise ratio

and from different orientations of the edge-artefacts in the single measurements. The measured differences are well below one voxel-size. Only in the region where there are carbon-fibres or traces of glue (for the fixation of the reference spheres) instead of aluminium there are larger deviations because of the different grey-levels. The right panel shows the difference of the surface from the assembled-state measurement to that from the averaged reference. The systematic deviations are mainly caused by beam-hardening.

In this chapter we gave only a brief glimpse on dimensional measurements and their analysis. For a real quantitative investigation it is necessary to use tactile measurements of the surfaces. There is a dedicated article focussing on this topic by M. Bartscher et al., also in this volume ([3]).

4. Summary and Conclusions

We presented a new test-specimen for both dimensional measurement and defect detection with CT. An industry-near work-piece was divided into suitable segments and reference geometries were applied which allow the alignment of individual measurements to those in the assembled state. With this procedure it is possible to create test-pieces for which reference data for defect and dimensional measurements can be obtained.

The new method to compare defect detections from different measurements described here allows individual analysis of every single defect. By using a multi-orientation measurement we improved the signal-to-noise ratio and reduced disturbances by CT-artefacts in the single measurements.

The reference measurements can also be used to extract a reference surface of the object. This surface can be compared to that from the assembled-state measurement to study the effects of certain CT-artefacts and of the reduced spatial resolution. A really quantitative analysis of the dimensional measurement is only possible with a reference data-set obtained by tactile measurements.

[1] M. Bartscher, U. Hilpert, F. Härtig, U. Neuschaefer-Rube, J. Goebbels, A. Staude, Industrial Computed Tomography, an Emerging Coordinate Measurement Technology with High Potentials, Proc. of NCSL International Workshop and Symposium / 3.-7.08.2008 / Orlando (FL), USA

[2] A. Staude, K. Ehrig, J. Goebbels, M. Bartscher, U. Hilpert, M. Koch, Methode und Prüfkörper zum Nachweis von Gussdefekten in Aluminiumbauteilen mit Computertomographie, Proc. of DGZfP-Jahrestagung 2009, 18.-20.05.2009, Münster/Germany, Berichtsband 115-CD

[3] M. Bartscher, M. Neukamm, M. Koch, U. Neuschaefer-Rube, A. Staude, K. Ehrig, J. Goebbels, Ch. Kuhn, A. Deffner, A. Knoch, Performance assessment of geometry measurements with micro-CT using a dismountable work-piece-near reference standard, Proc. of ECNDT 2010, 7.-11.06.2010, Moscow, Russia, this volume