

# Application of an Industrial CT Reference Standard for Cast Freeform Shaped Workpieces

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**Abstract.** Industrial computed tomography (CT) today is an important method to analyze defects and to measure the geometry of technical products. The measurement capability of industrial CT often depends on the knowledge of the measurement errors being present. Only with this knowledge, effective corrections are possible by manufacturers, or adapted measurement procedures become possible for the customers. Thus, there is the strong need to have adequate reference standards both for the assessment of general dependencies and for the measurement of task-specific effects. Especially the latter are difficult to assess. This paper shows the application of a versatile dismountable workpiece-near reference body for the use with CT. The reference standard was made from a miniaturized cast aluminium (one-)cylinder head. It can be dismounted into four segments, each featuring reference geometries which enable a registration of CT measured and other reference datasets (e.g. from tactile CMM). The reference standard embodies complex freeform surfaces which are a challenging measurement task for CT and other sensors. Here the application of the reference standard is the study of the influence of material mixes. This is realized by adding pieces of other materials which disturb the mono-material measurement. Results of the application of the reference standard are presented using data from industrial micro-CT systems and CMM reference data. A special emphasis is given on the workflow of the data processing and the data analysis.

## 1. Introduction

Industrial computed tomography (CT) today is a versatile and important non-destructive testing and dimensional measurement technology. The measurement capability of industrial CT often depends on the knowledge of the measurement errors being present. Only with this knowledge, effective corrections are possible by manufacturers, or adapted measurement procedures become possible for the customers. Thus, there is the strong need to have adequate reference standards both for the assessment of general dependencies (e.g. scaling factors or beamhardening effects) and for the determination of task-specific effects. Especially the latter are difficult to assess. Often it is not possible to simply calibrate a real workpiece as a master part. By the use of such a simple master part many effects are not covered. Another challenge of dimensional CT is the measurement of multi-material workpieces. Artefacts, i.e. measurement errors induced by the material composition, are frequently observed for this case. The current workflow for the data analysis does usually not treat these effects. This paper shows the application of a versatile dismountable workpiece-



near reference body for the use with CT. The analysis is focused on the freeform properties of today's workpieces and on the aspect of multi-material bodies. In the following the data and analysis workflow is illustrated.

### 1.1 Metrological traceability

Metrological traceability often is unequal to the colloquial use of "traceability". The former means that for dimensional measurements results are traceable to the SI unit "meter". Thus, there exists a continuous calibration chain which a measurement uncertainty renowned in each step. For complex measurements systems traceability is often not accomplished for all measurements; i.e. the device is not traceable. Examples are the measurements of freeform shaped workpieces in coordinate metrology. Here nearly all measurements, i.e. using tactile probes, optical sensors and CT, are not traceable as no adequate statement on the measurement uncertainty exists.

For complex measurement techniques like CT it is instructive to consider the general influences on the measurement uncertainty. ISO 15530-3 describes a method for the empirical assessment of the measurement uncertainty using reference measurements and groups the influences in four sections: the uncertainty of the reference measurement (calibration uncertainty), the standard uncertainty of the process itself (repeatability), the uncertainty of workpiece contributions and uncertainty contributions due to systematic errors. Currently a rewriting of the ISO 15530-3 is in progress as the 2004 standard does not treat systematic errors in a GUM [1] conformant way [2]. For dimensional CT as an example of a complex measurement technique one should analyze which measurement method and principle is set as reference. The standard use is to set tactile measurements as reference. In the following effects for tactile reference measurements and the influence of the workpiece material on CT measurements are discussed.

### 1.2 Reference standards

A usual way to analyze the properties of measurement systems is to use reference standards (material measures). Certain reference standards have been developed in the past for dimensional CT which have found their way in the standardization (VDI/VDE 2630-1.3) (e.g. Fig. 1 & 3).



**Fig. 1.** Calotte cube made from titanium, size  $(10 \text{ mm})^3$



**Fig. 2.** PMMA cylinder with spherical landmarks [3], total size  $\varnothing 20 \text{ mm} \times 108 \text{ mm}$  (visible here top 30 mm), diameter of spherical landmarks 0.5 mm



**Fig. 3.** Micro tetrahedron made from 4 ruby spheres of size 0.5 mm

Applications for these dedicated reference standards are verification, error assessment and correction. But there is an important drawback of these bodies. Their features are not similar to work pieces and no freeform geometries are present.

### *1.3 Freeform reference standard*

A dismountable freeform reference standard made from a cast miniaturized aluminium cylinder head (cast of ACTech GmbH, Freiberg/Saxony, Germany) has been created by PTB. It can be dismounted into four segments, each featuring reference geometries (spheres mounted on carbon fibre rods and cylinders) which enable a registration of CT measured and other reference datasets (e.g. from tactile CMM). The reference standard embodies complex freeform surfaces which are a challenging measurement task for CT and other sensors. Moreover, the standard enables the study of properties of CT measurements in the interior of the geometry. This part has been used to analyze the properties of CT for non-destructive testing [4] and for dimensional measurements [5]. In this work one segment (identification 1A1) of the dismountable reference standard is used to analyze CT measurements in a multi-material configuration. For an estimation of the surface roughness of the segment 1A1 we measured roughness  $R_z$  ranging from 2  $\mu\text{m}$  to 135  $\mu\text{m}$  and pure sand cast domains with average  $R_z$  of 81  $\mu\text{m}$ .

## **2. Metrological aspects of freeform geometries**

### *2.1 Tactile probing of freeform surfaces*

The tactile probing of a freeform surface is a challenge as it requires the correct mechanical probing of the surface, the correct probe radius correction, the correct point determination and possibly the treatment of morphological filtering of the tactile probe itself. Any tactile measurement of a freeform surface has to ensure that all these steps and influences have to be properly handled. Thus, it is essential to perform the measurement with a known probe tip radius – which is usually easy to achieve for round probe tips by a proper probe qualification – and by knowing the real surface normal at the measurement point. The latter is difficult as this normal vector usually is not known for the specific part. There exist several approaches to assess or approximate the surface normal of the real part. The most commonly used method is to approximate this normal by CAD given information. This method can result in strong measurement errors for the case that the part deviates significantly from the CAD model as it is the case for bigger production deviations or stock outage. The second possibility to assess the normal of the part is to use “force vector” information which is given as internal information with certain coordinate measuring machines (CMM). The use of these data is critical as the vector of the probing force can differ significantly from the real surface normal. A recent study has shown deviations up to 25° using a high precision CMM with recent control software for the probing of a sample surface with precisely known surface normal. These deviations can cause significant measurement errors when the force vectors are used for point evaluation. Thus, this internal information must not be used. The third method to assess surface normal information of a specific part is the empirical assessment of this normal by respective measurements and possibly by an iteration. Only an empirical assessment can ensure a reliable measurement for freeform surfaces.

### *2.2 Empirical assessment of the surface normal for freeform parts*

For the empirical assessment of the surface normal of a freeform surface it is possible to use a built-in probing procedure of the CMM or to perform a free programming of the prob-

ing and the data evaluation process. An iterative procedure using mainly a built-in function of a Carl Zeiss CMM and the software Calypso has been described in [5]. Here a measurement of three points (tripod) and approximation of the surface by a plane is applied. The resulting data point is assessed by the probing of the CMM at the centre of the tripod as the estimated contact point with the use of an approximated surface normal given by the three tripod points, i.e. no projection on the nominal position is performed.

An enhanced probing scheme may be implemented in future by the use of an adapted model and by point assessment without projection to nominal point. The objective here is to have a good local approximation of the surface, a free data sampling (i.e. no restrictions for the number of points) and a statement for the uncertainty of the parameters of the model. One approach which meets all three points is the fitting of a quadric to the free-form surface [6].

### *2.3 Proper actual-nominal value comparison*

As (false) standard scheme for nominal-actual comparison of CT and CMM data tactile CMM measurement points are usually set as actual and CT surface are usually set as reference (nominal value). This can lead to wrong results as shown in [5]. The correct scheme is to set the tactile CMM measurement point and assessed surface vector as reference (nominal value) and CT surface as actual. This process requires appropriate inspection software and – of course – the knowledge of the surface normal. In [5] the inspection software ATOS 6.2 (Fa. GOM, Braunschweig, Germany) has been used. In the following the data analysis is performed with the successor software GOM Inspect V7 SR2.

### *2.4 Roughness influence & local data analysis*

The workpiece roughness influences any dimensional measurement. The precise contribution to the measurement either as a statistical influence to the measurement uncertainty or a contribution to a systematic deviation has to be analyzed for each sensor. Up to now the roughness influence for CT has only been analyzed for selected cases [7].

Recently statements are made for dimensional CT relating the voxel size to the measurement uncertainty. Here a range of values down to 1/10 of a voxel edge size in minimum are stated for CT data sets of good quality [8]. These ratios may only be reached under certain conditions: e.g. mono-material measurements, flat surfaces without significant roughness, the absence of geometry induced artefacts and measurands where a massive averaging of properties occurs. Examples are the diameter of a cylinder which is measured with a high number of points (e.g.  $\gg 25$  points), where the cylinder is located inside one single material and is located far away from disturbing structures like edges. It has to be stressed that the above mentioned ratios cannot be reached for the cases where the roughness of the surface is not negligible compared to the voxel edge length and where no or only a small averaging of the measurand occurs. The worst case is the local analysis, i.e. the single point measurement, of a workpiece with strong roughness. The local analysis can detect certain spatial properties and deviations of the measurement, but it is interfered with surface effects. Thus, deviations of the order of the voxel size may occur.

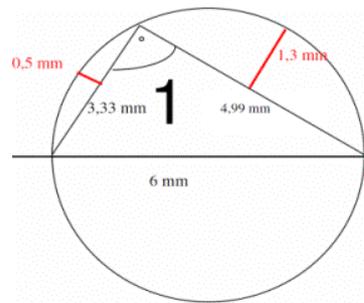
### 3. Multi material analysis

#### 3.1 Modification of segment 1Al with ZTA spheres

The objective for performing better multi-material measurements with CT is to describe an optimized work flow for the dimensional analysis. Additional to the features of the segment 1Al we have added three raw unpolished ZTA (Zirconia Toughened Alumina) spheres with a diameter of 6.1 mm containing 86%  $\text{Al}_2\text{O}_3$  and 14%  $\text{ZrO}_2$  to the segment 1Al to study material effects and effects related to the local workpiece topology. The ZTA spheres have been fixed at the segment 1Al with locking varnish. In radiographic simulation of a 205 kV X-ray tube spectra with BAM software aRTist [9] they showed 50% more absorption compared to Al which allows good conditions for CT measurements. In CMM measurements with 1048 points these spheres showed large form errors of 66  $\mu\text{m}$  to 138  $\mu\text{m}$ . Two flat faces have been machined to the ZTA spheres (Fig. 4 and 5), respectively, to allow a registration of the bodies. Finally, a laser marked number (label 1 to 3) has been added (Fig. 4). For registration we used the two flat faces for primary and secondary registration and the gauss fitted centre point of the sphere as origin (tertiary registration).



**Fig. 4.** ZTA (Zirconia Toughened Alumina) spheres with a diameter of 6.1 mm containing 86%  $\text{Al}_2\text{O}_3$  and 14%  $\text{ZrO}_2$



**Fig. 5.** Vertical cut through ZTA 1 sphere with  $90^\circ$  angle between two flat faces used for registration

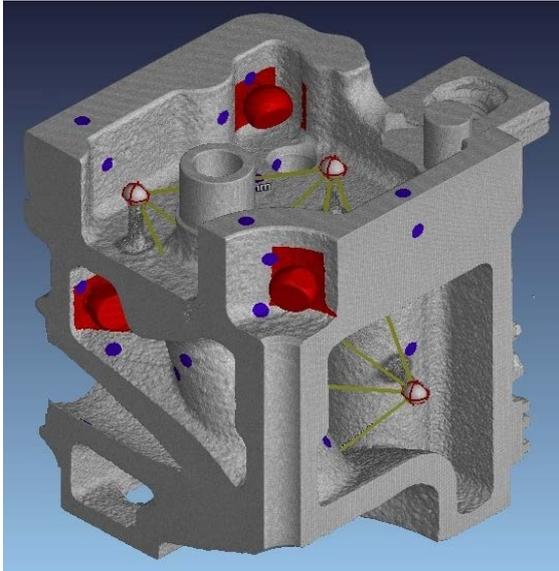


**Fig. 6.** Three mounted ZTA spheres on segment 1Al; ZTA 1 sphere is visible on bottom left

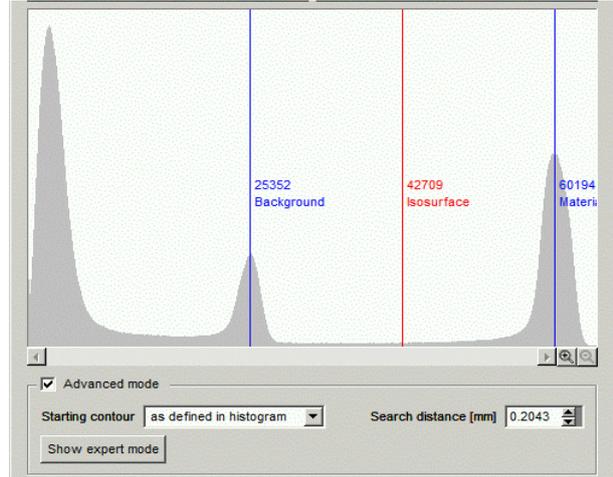
Fig. 6 shows the mini-cylinder head segment 1Al with attached three ZTA spheres. In the following the influence of materials ZTA to Al and Al to ZTA is analyzed.

#### 3.2 Work flow

The workflow starts with data analysis in VolumeGraphics StudioMax 2.1: Scaling correction has been performed using the distance of the 5 reference spheres. Afterwards a second reconstruction with correct scaling has been performed. The CT volume has been aligned to tactile CMM coordinate system using the 5 reference spheres. ROIs (region of interest) have been created around ZTA spheres and around patches at the aluminium surface for individual surface determination using adaptive threshold in VGStudioMAX 2.1 (Fig. 7 and 8).

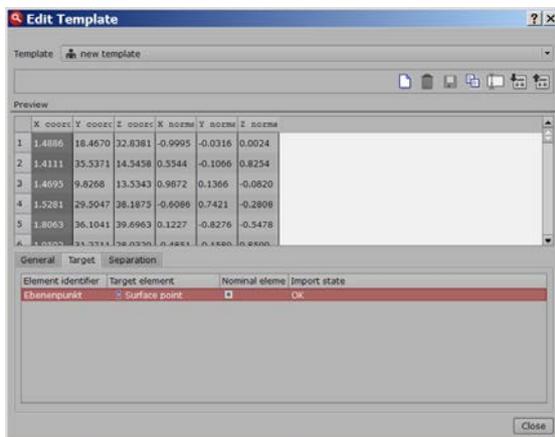


**Fig. 7.** Surface rendered CT data with ZTA ROIs (red), surface patches (blue) and ruby spheres (grey / red)

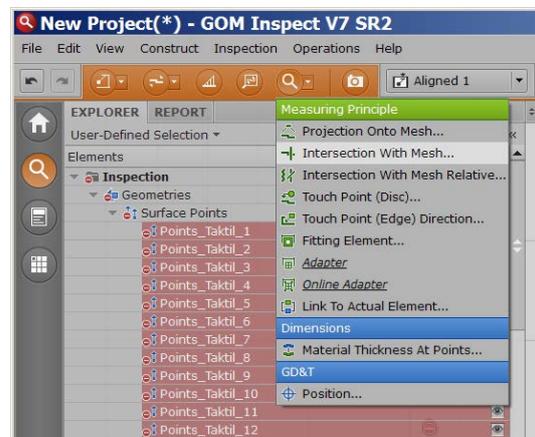


**Fig. 8.** Histogram of extracted ROI volume of ZTA 1 sphere. The aluminium peak is set as background, while the ZTA peak is set as material (both as starting values for following adaptive surface determination)

Finally, we calculate the deviations relative to surface normal of the 1135 tactile data points for each ZTA sphere in GOM Inspect V7 SR2 or for the 34 respective patches of the aluminium body (see section 4.2). The main advantage here is the capability of this new software to analyse now datasets with several thousand data points of type surface point as target import format (i.e. using point and normal as surface point and setting it as nominal element, cf. Fig. 9). Despite a warning of the software (for datasets of more than 200 points) successful inspections have been performed with at least 3000 points. The last step in the analysis – which is essential for a correct inspection – is to define the measurement principle as “Intersection with Mesh” (Fig. 10). Using the normal of the CMM measured data point deviations are calculated as a vectorial intersection of the mesh of the CT dataset. Thus, an “air gap” between CT dataset mesh and tactile data points results in a negative deviation as the error vector is anti-parallel to the correct normal of the tactile CMM data. As common to inspection software results can be displayed (see e.g. Fig. 16) or exported as table.



**Fig. 9.** Surface point in GOM Inspect V7 SR2 as target import format (visible after editing the import template)

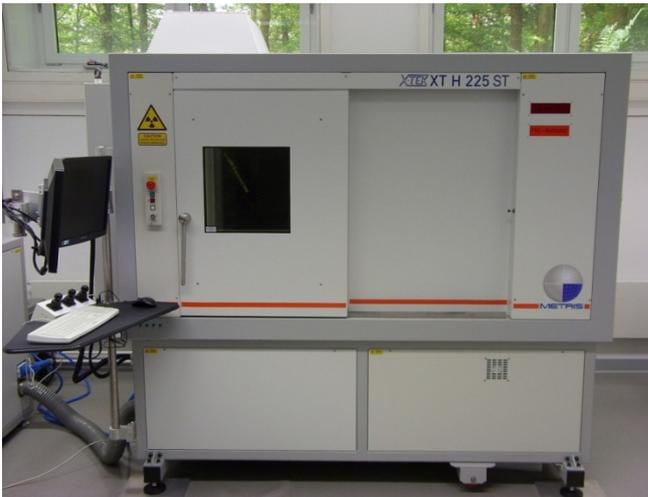


**Fig. 10.** “Intersection With Mesh” is applied in GOM Inspect V7 SR2 as measuring principle

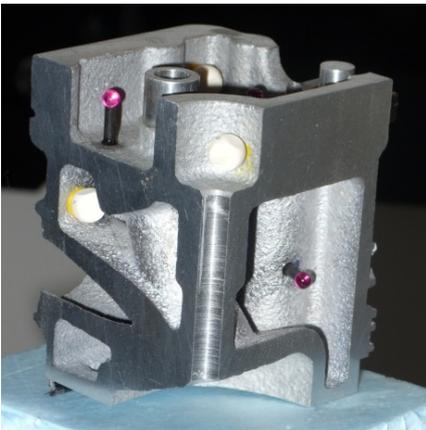
## 4. Measurements & Results

### 4.1 CT Measurement setup & parameters

CT measurements of the 1Al segment with added ZTA spheres (Fig. 6) have been performed with two in almost all parameter different setups at PTB and at BAM. At PTB we used the NIKON Metrology XT H 225 ST CT system (Fig. 11) with reflection target and 210 kV setting, 1.9k x 1.5k Varian PaxScan 2520 detector, detector filter 1 mm Cu, 3016 angles with a voxel size of  $(54 \mu\text{m})^3$  and sample orientation (nearly) “top up” as shown in Fig. 12. At BAM we used a CT system with reflection target and 205 kV setting, filter 0.5 mm Cu + 0.75 mm Ag, 1800 angles with a voxel size of  $(50 \mu\text{m})^3$  and sample orientation “horizontal tilted” as shown in Fig. 13.



**Fig. 11.** PTB NIKON Metrology XT H 225 ST CT in Braunschweig, Germany



**Fig 12.** Setting of the PTB CT measurement P00027 with parameters 210 kV, filter 1 mm Cu, 3016 angles, voxel size  $(54 \mu\text{m})^3$



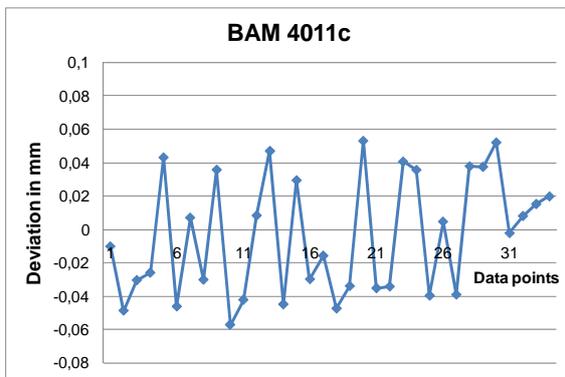
**Fig 13.** Setting of the BAM CT measurement 4011c with parameters 205 kV, filter 0.5 mm Cu + 0.75 mm Ag, 1800 angles, voxel size  $(50 \mu\text{m})^3$

For analysis of ZTA spheres unfiltered, unaveraged CT volume data have been used. BAM has applied a 3x3 median filter on projection data before reconstruction. Tactile CMM data have been assessed using a Zeiss UPMC 1200 Carat CMM. For the tactile CMM measurements we used single point probing and a probe tip diameter of 0.6 mm. The measured form error of ZTA 1 sphere on 1048 points was 76  $\mu\text{m}$ . The CMM measurements of the ZTA spheres have been performed as measurements of a regular geometry. Synthetic

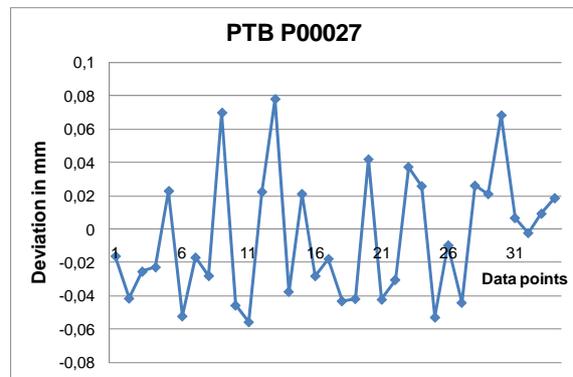
surface vectors have been added to the point data to allow a symmetric data analysis compared to the analysis of the patches of the aluminium body (cf. following section).

#### 4.2 CT Results for segment 1A1 (patches on Al surface only)

The workflow described in section 3.2 has been applied to the 34 patches of the aluminium material of the segment 1A1. Geometry and location of the patches has been described in [5]. For each patch of diameter 1 mm one tactile data point with corresponding surface normal has been measured with a probe tip diameter of 2 mm using the iterative probing scheme described in [5]. The analysis performed of the recent CT data sets is performed with GOM Inspect V7 SR2. Fig. 14 and 15 show the respective deviations between the tactile measurement as reference and the CT measurements of BAM and PTB as actual. No significant difference is visible in comparison of the results presented in [5]. Thus, it can be concluded that the influence of the ZTA spheres upon the aluminium is not dominant.



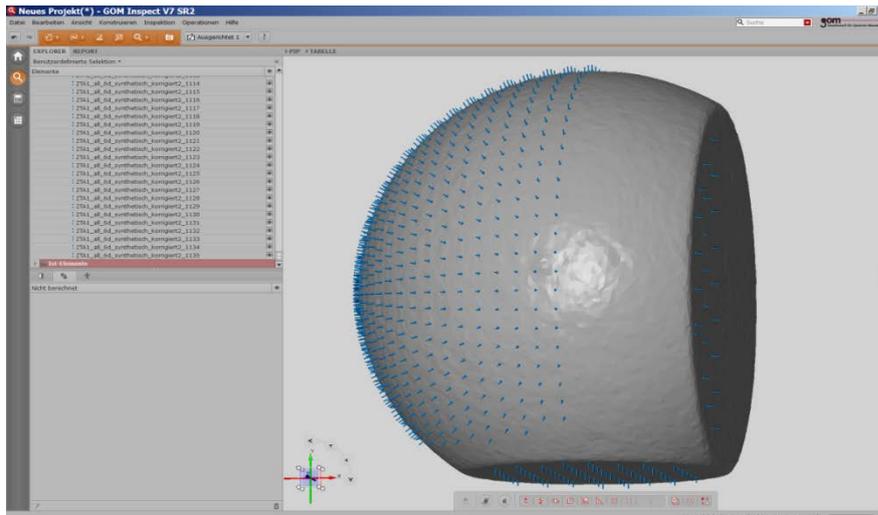
**Fig. 14.** Deviations between tactile and CT data points for BAM 4011c measurements; analysis of 34 surface points on aluminium



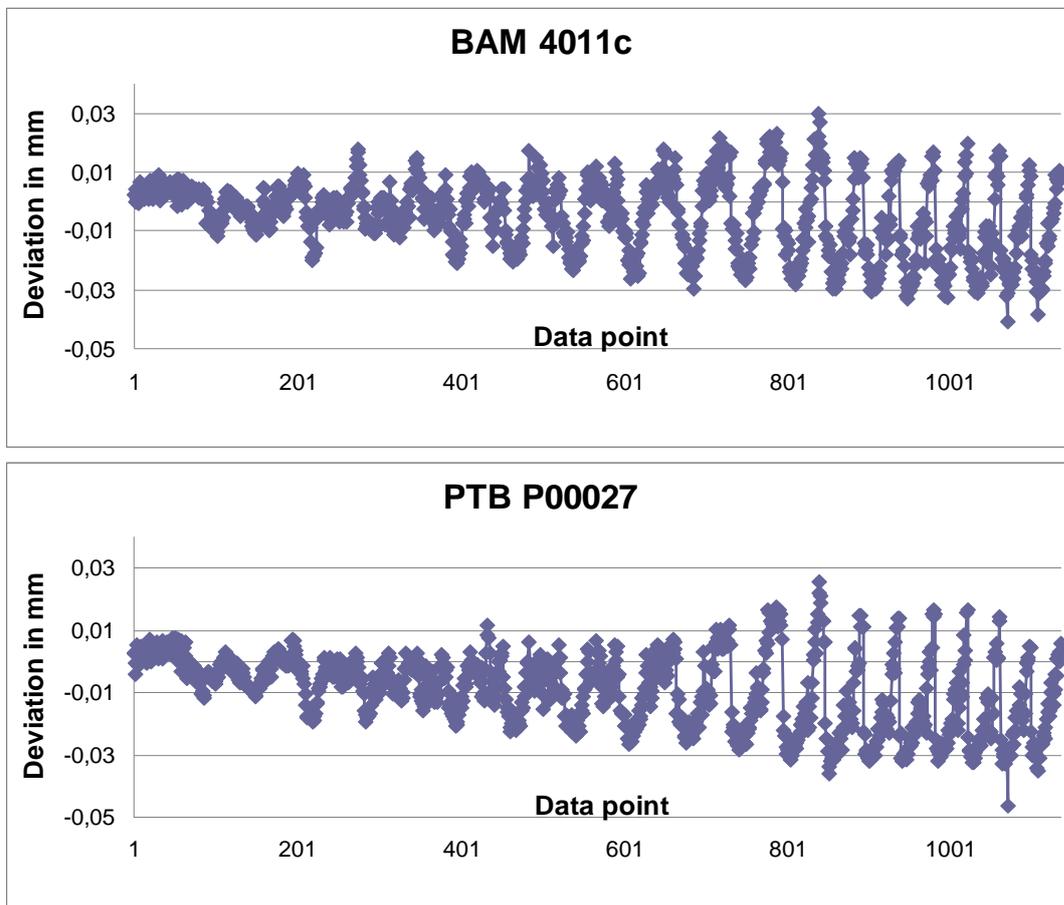
**Fig. 15.** Deviations between tactile and CT data points for PTB P00027 measurements; analysis of 34 surface points on aluminium

#### 4.3 CT Results for ZTA 1 sphere

The deviation of the ZTA spheres of the BAM CT measurement 4011c and the PTB CT measurement P00027 relative to the tactile CMM measurement have been analysed as described in section 3.2 . Fig. 16 shows as an example the detailed view of a state after performing the analysis in GOM Inspect V7 SR2 of ZTA 1 sphere to which the analysis is restricted here. Fig. 17 finally contrasts the deviations of the PTB and BAM measurements with the respective tactile CMM measurement.



**Fig. 16.** Surface point and measurement deviations of ZTA 1 sphere as shown in GOM Inspect V7 SR2



**Fig. 17.** Deviations between tactile and CT data points for BAM 4011c (top) and PTB P00027 (bottom) measurements (first 84 data points are planar regions; negative deviation means an air gap between tactile measurement and CT data)

The deviation analysis of tactile and CT data points showed high correlations (correlation coefficient of 0.9) between observed residual deviations of the two CT measurements (see Fig. 17). Due to the completely different CT setups this result is a good indication for a valid surface determination of the CT measurements. Additionally, no special anisotropy can be seen in the analysis of ZTA 1 sphere at the interface to the Al material. Neverthe-

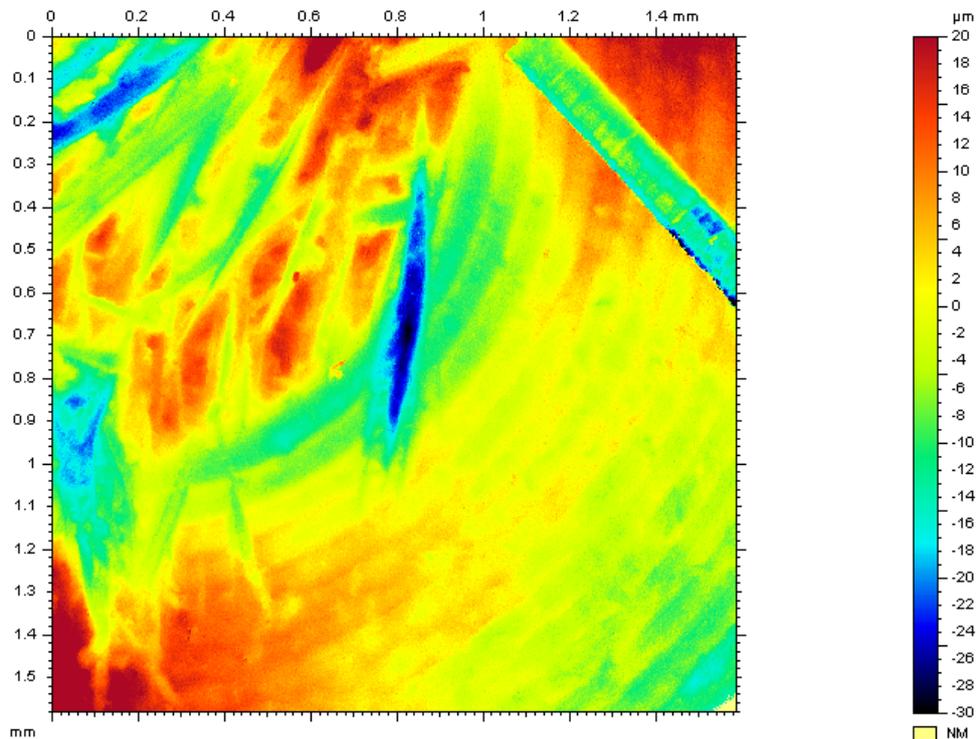
less, deviations in the order of 70% of the voxel size are to be observed relative to the reference measurements. Thus, a deeper analysis of the effects is necessary.

#### 4.4 Optical measurement with confocal measurement system

In order to analyse the deviations between CT measurements of the ZTA spheres and tactile reference data further measurements with independent optical sensors have been performed. It is well known that optical sensors show up new effects respective surface sensitivity. Thus, these measurements can only give a limited view to the present topography of the ZTA spheres. Measurements have been performed with various optical sensors including white light interferometry, focus variation and confocal measurements.

Only the confocal measurement system (nanofocus  $\mu$ surf) was able to assess reasonable surface data. This became visible with a measurement of one flat face of ZTA 3 sphere. The observed deviations of the confocal measurement system of  $\pm 2\mu\text{m}$  correspond sufficiently with the tactile reference data (2-3  $\mu\text{m}$  observed form deviation). Other optical sensors failed due to strong surface effects. This result is not surprising as standard aluminium oxide ceramics (without added zirconium oxide) shows a significant volume scattering effect which hinders many optical measurements.

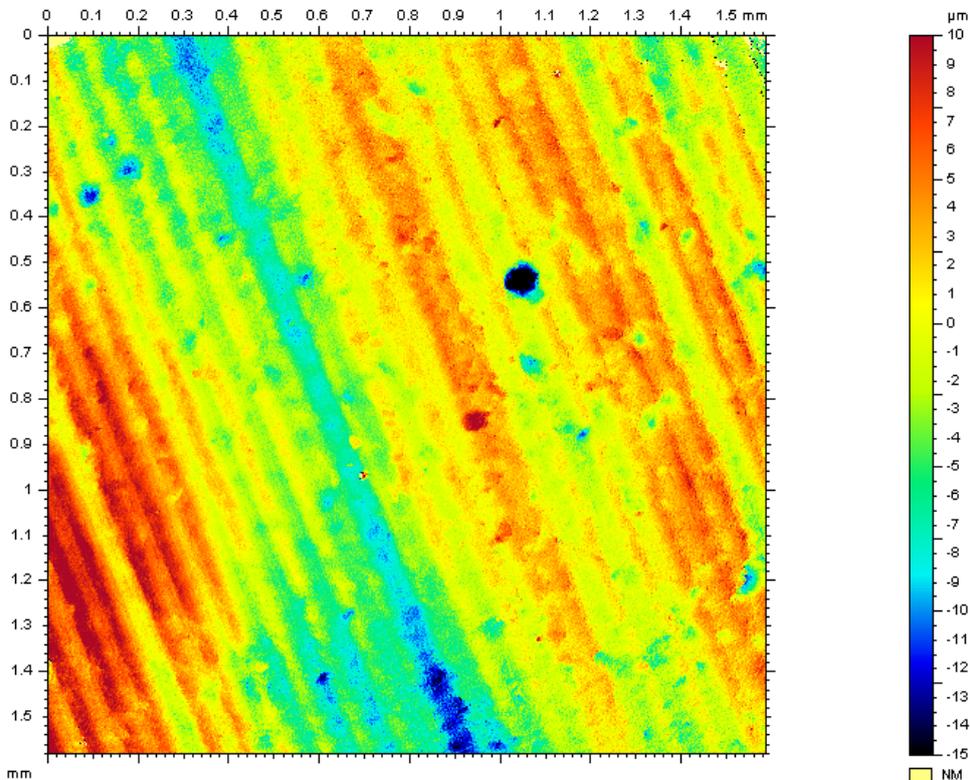
Fig. 18 shows as a result of the confocal measurement the surface topography of the ZTA 1 sphere after subtraction of the main radius of the raw sphere. Due to the mounting of the spheres to the segment 1A1 (see Fig. 6, 12 and 13) only a “top” view is possible for the respective optical measurements. A distinct surface full of scratches and grooves can be seen on ZTA 1 sphere. The scratches are visible as an isolated effect of the ZTA 1 sphere.



**Fig. 18.** Optical measurement with confocal measurement system of ZTA 1 sphere. Sample view of field size 1.6 mm x 1.6 mm with subtracted Gaussian fit sphere; visible bar of the laser mark “1” in top right corner

With the naked eye fine circular structures are visible on all three spheres. The structures can also be identified at the edges of Fig. 18 (cf. edge bottom right). Confocal measurements of ZTA 3 sphere (Fig. 19) clearly showed these circular structures which correlate to periodical oscillations of tactile and CT comparison (see Fig. 17). Due to the

subtraction of the main radius and due to the measurement position near the meridian the circular structures appear as straight lines in the visible result of Fig. 19. These structures are a result of the manufacturing process of these raw spheres.



**Fig. 19.** Optical measurement with confocal measurement system of ZTA 3 sphere. Representative view of field size 1.6 mm x 1.6 mm with subtracted Gaussian fit sphere

## 5. Conclusions

Surface roughness and workpiece topology can influence the properties of dimensional CT measurements. The dismountable reference standard can be used to analyze the influence of surface roughness and workpiece topology, to analyze the influence of data processing and to test e.g. enhanced probing schemes for freeform surfaces. The study presented here illustrates the benefits of using reference standards embodying complex features also for the application multi-material analysis. The results clearly indicate the above influences in cases where e.g. the surface roughness is no longer negligible compared to the voxel size of the CT measurement. Further analysis is necessary to achieve a match between CT data and tactile data also for rough surfaces, e.g. by the analysis of the morphological filtering of the single probes. An advanced modelling of surfaces can help to improve the tactile probing of rough or highly curved surfaces.

## 6. Acknowledgement

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## References

- [1] JCGM 100:2008: GUM 1995 with minor corrections, Evaluation of measurement data — Guide to the expression of uncertainty in measurement. First edition, BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML, 2008
- [2] Härtig, F.; Krystek, M.: Correct treatment of systematic errors for the evaluation of measurement uncertainty. Proc. of ISMTII 2009, Saint-Petersburg, Vol 1, p. 1-016 – 1-019, 2009
- [3] Neukamm, M.; Schulze, M.; Staude, A.: Untersuchung der geometrischen Eigenschaften industrieller CT mit Hilfe eines neuartigen Prüfkörpers und den Methoden der Photogrammetrie. BB 122-CD DGZfP-Jahrestagung 2010 ZfP in der Forschung, Entwicklung und Anwendung, 10. - 12. Mai 2010, Erfurt, 2010, <http://www.ndt.net/article/dgzfp2010/Inhalt/di2a2.pdf>
- [4] Staude, A.; Goebels, J.; Ehrig, K.; Bartscher, M.; Koch, M.; Neuschaefer-Rube, U.: A new test piece for geometry and defect measurements with micro-CT. Proc. of European Conference for non-destructive Testing ECNDT 2010, Moscow, Russia, 5-11 June 2010
- [5] Bartscher, M.; Neukamm, M.; Koch, M.; Neuschaefer-Rube, U.; Staude, A.; Ehrig, K.; Goebels, J.; Kuhn, Ch.; Deffner, A.; Knoch, A.: Performance Assessment of Geometry Measurements with Micro-CT using a dismountable work-piece-near reference standard. Proc. of European Conference for non-destructive Testing ECNDT 2010, Moscow, Russia, 5-11 June 2010
- [6] Bartscher, M.; Neukamm, M.; Krystek, M.: Method for a Traceable Geometry Assessment of Arbitrarily Shaped Sculptured Surfaces. Proc. of 10th International Symposium on Measurement and Quality Control ISMQC, Osaka, Japan, 5-9 September 2010, ISBN 978-4-9905119-0-6
- [7] Fiedler, D., Bartscher, M., Hilpert, U.: Dimensionelle Messabweichungen eine industriellen 2D-Computertomographen: Einfluss der Werkstückrauheit. DGZfP-Proc. BB 89-CD, 2004
- [8] Reinhart, C.: Industrial CT & Precision. Conference in “Application of CT Scanning in Industry” at Danish Technological Institute, Taastrup, 31. May 2011
- [9] Gollwitzer, C.; Bellon, C.; Deresch, A.; Ewert, U.; Jaenisch, G.-R.: On POD Estimations with Radiographic Simulator aRTist. Proc. of International Symposium on Digital Industrial Radiology and Computed Tomography DIR2011, Berlin, 20.-22. June 2011