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Report on CT-measurements of injection nozzles

Report for

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Advanced Computed Tomography for dimensional and surface measurements in industry – AdvanCT

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Overwiew

In the case study, a part of a Bosch injection nozzle (Figure 1) was measured. The measurement tasks were to determine the outside diameter, as well as the diameter and cone angle of the injection holes. These consist of a cylindrical pre-stage (∅ 300 µm) and the conical nozzle (∅ 150 µm). The CT measurements were carried out using PTB's CT system. In addition, tactile reference measurements were carried out with a Renishaw SP25 probe as well as Werth fiber probes. Furthermore, CT measurement results from Bosch, which were determined with a CT system from Werth, were available.

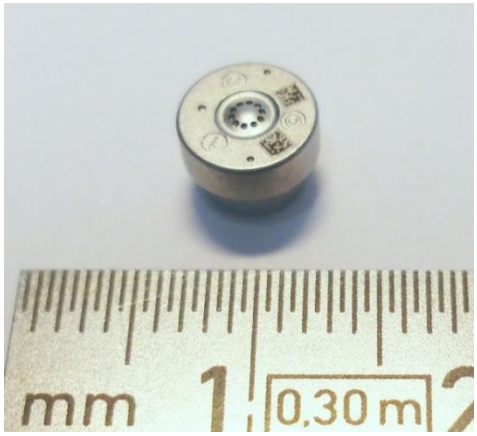


Figure 1: Measured injection nozzle

1. CT measurement in PTB

1.1 Principle

The measurements were carried out with PTB´s CT system Nikon MCT 225.

The measurement parameters were:
U_{Tube}= 189 kV, I_{Tube}= 37 µA, integration time of image acquisition: 2000 ms, no filter.

The geometrical parameters were:
SDD = 1174.000 mm, SOD = 35.2675 mm, voxel size = 6.00809 µm
The voxel size has been determined applying the method validated in A1.1.1 using a calibrated Invar hole foil with a grid edge length of 7.5 mm. The relative uncertainty of the optical calibration of the foil is approx.$1 \cdot 10^{-5}$.

The dominant contributor to the uncertainty of the scale is the uncertainty of $\Delta SOD/SOD = 5 \cdot 10^{-5}$ caused by errors of the rotation stage, source drift and the short-term reproducibility of the object stage position which is 1.5 µm.

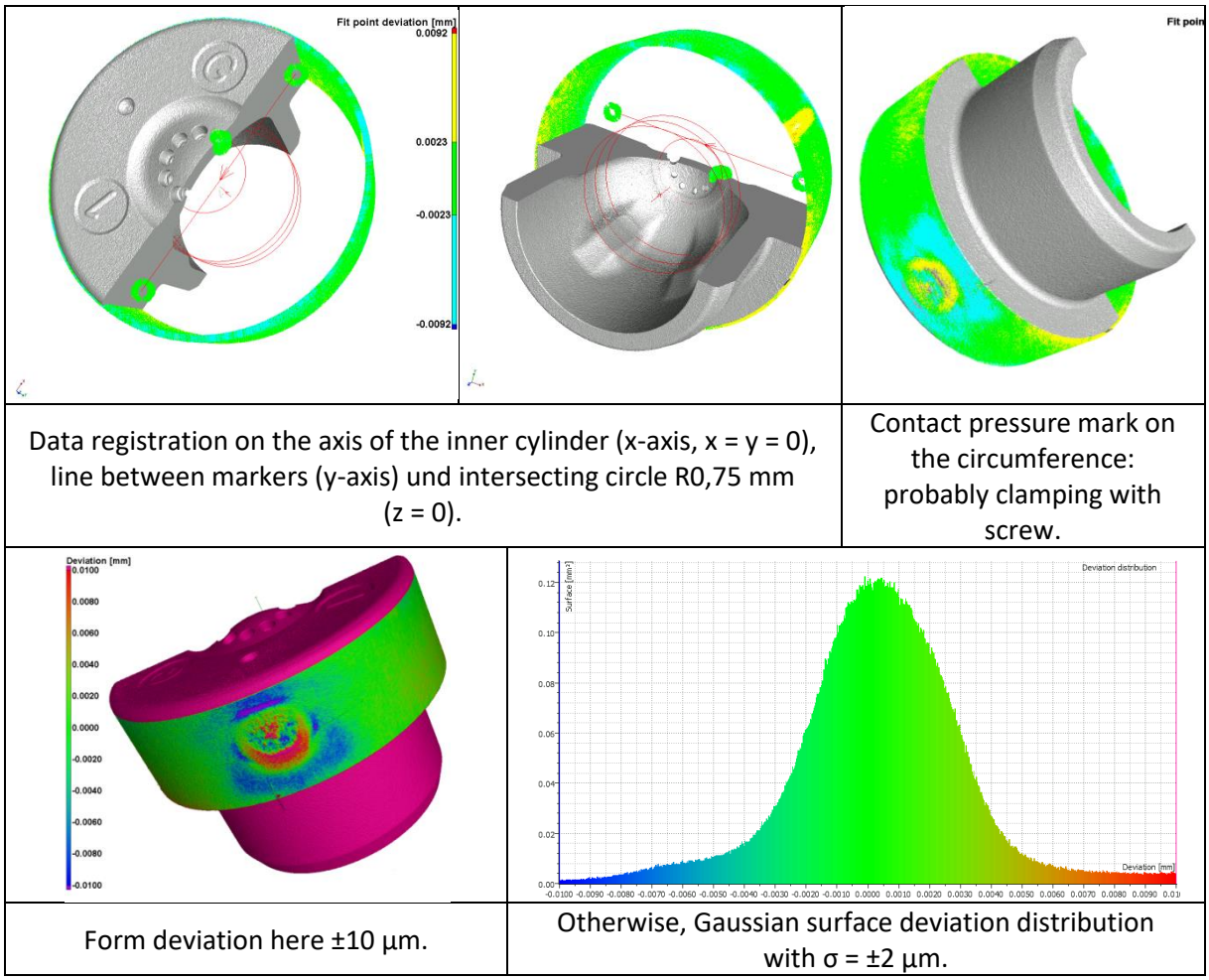
The image stack was generated by a C# program using the IPC control library (Form10.cs): Automatically, an averaged (32x) white image was captured before/after the scan. A total of 1900 images were taken, each averaged over 2 s. 1800 images correspond to one full rotation resulting in a forerun of 100 images. Single images were acquired with the stationary rotation stage and one image discarded afterwards so that no image lag occurs.

The gain correction was applied to the image stack using the two white images and saved in the "cor" subdirectory.

The image deconvolution correction was performed with known parameters and stored in the subdirectory "dc" with the file name extension "cordc".

The reconstruction was done with NIKON software CT Pro 3D 5.2.2. The last 1800 images were used and Nikon beam hardening correction level 2 was applied as well as a custom beam hardening correction.

The volume data was evaluated with VG Studio Max V3.03 64 bit. The registration of the data is shown in Fig. 2.



Data registration on the axis of the inner cylinder (x-axis, x = y = 0), line between markers (y-axis) und intersecting circle R0,75 mm (z = 0).

Contact pressure mark on the circumference: probably clamping with screw.

Form deviation here ±10 µm.

Otherwise, Gaussian surface deviation distribution with σ = ±2 µm.

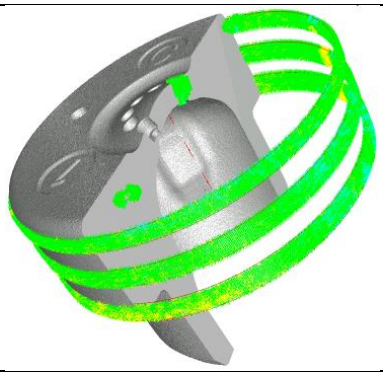
Figure 2: Registration of the data, form deviation

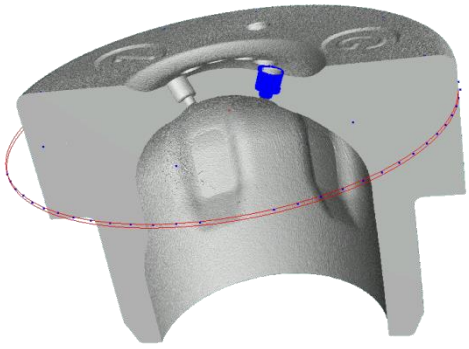
The comparison with tactile measurement data ("Mesh3") was carried out in the VGL project. These data were obtained using a Werth VideoCheck UA CMM with a 2D fiber probe (nozzle) and a Renishaw SP 25 type probe (outer cylinder).

The determination of roughness was performed with an Alicona G5 instrument and showed the roughness on the outer cylinder. The tactile measurements thus indicate a 2.0 µm too high (enveloping) surface compared to the CT.

1.2 Results

The scale of the CT measurement was verified with a measurement of the outer diameter of the part (see Fig. 3).





CT-measurement

radius in µm	
full cylinder	2990.2
ring at the top	2988.4
ring in the middle	2990.6
ring at the bottom	2991,0

comparison tactile measurement - CT

radius in µm	
Tactile ring*)	2991.8
CT ring**)	2989.0

*) measured with probing sphere diameter 1 mm
**) Position on the front ring at the end towards the center ring

Figure 3: Results of the measurement of the outer diameter

The tactile probe performs an analog morphological filtering of the roughness profile of the surface. A graphical estimate of the effect of this filtering on the measured diameter is shown in Fig. 4 based on an optical profile measurement.

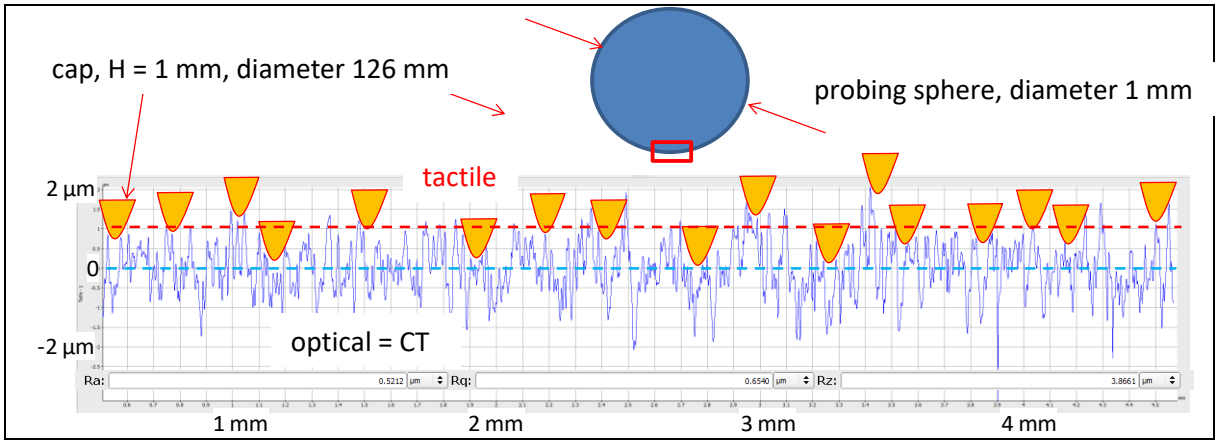


Figure 4: Influence of roughness on the measurement of the outer diameter. The tactile measurement with a probe ball of 1 mm diameter is approx. Rz / 4 = 1.0 µm too far to the outside compared to CT/optical.

If the measured tactile value of 2991.8 µm radius is corrected to 2990.8 µm, it still deviates from the CT value by +0.8 µm. The uncertainty of the tactile measurement itself is about 0.5 µm, so that a significant deviation must be assumed, which corresponds to a scale error of 2.5 10^{-4} in the CT, for example, or an offset of the surface determination of 1 / 7.5 voxels.

This is assumed to be a good estimate of the errors in determining the nozzle geometry, where the roughness of the nozzle bore is unknown. However, the roughness itself can be estimated with CT, insofar as there are no roughness components that exceed the structural resolution.

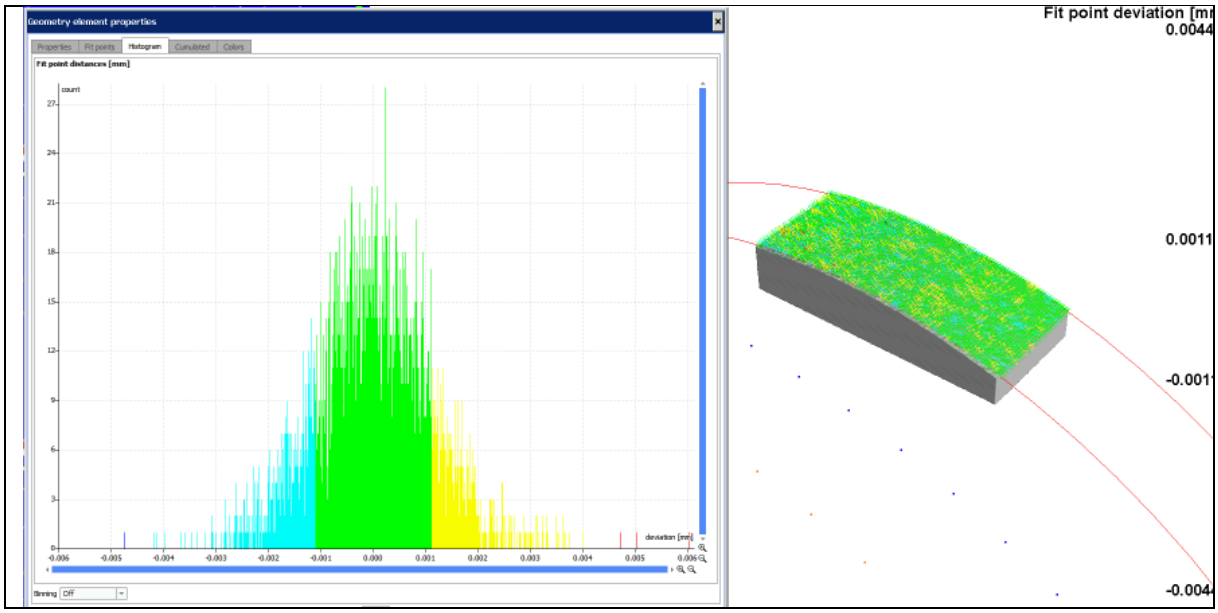


Figure 5: Roughness of the outer diameter measured with CT: A section of the cylinder surface has an apparent Rq value of 1.0 µm in CT, so assuming the tactile measured Rq value of 0.65 µm, the noise of the CT measurement is calculated to be $(1 - 0.65^2)^{0.5}$ µm = 0.76 µm. Thus, a significant portion of the longer wavelength texture (>2 voxels) is actually property of the specimen, as the CT noise is uncorrelated.

2. Comparison tactile - CT of nozzle geometry

2.1 Comparison tactile - CT measurement of PTB

Th nozzle geometry was measured on a Werth VideoCheck HA with 2D two-sphere fibre probe. The system operates better than specification due to careful calibration and good environmental conditions. The pre-stage and the nozzle were scanned sequentially; the effective probe sphere diameter was about 50 µm, so shaft probing can easily occur. One nozzle was chosen (see figure 2) to keep the measurement and adjustment efforts manageable.

The results of the tactile and CT measurements performed by PTB are shown in Figure 6 and 7. In Table 1 the measured diameters are compared.

There is an eccentricity of the nozzle to the pre-stage in the tactile data, which is not observed for any nozzle in the CT. It is therefore assumed that a shift in the coordinate system has occurred between the two measurements. There is also some rounding in the tactile data at the edges caused by the spherical shape of the probe tip.

Initially, only the mean inner radii are compared since the planes at the inlet and outlet as well as the centre plane between the injection hole and the pre-stage cannot be fitted in the tactile data. Therefore, when evaluating individual circles, it cannot be guaranteed to hit the same measurement planes. Centre radii are the result of the best-fit of a cylinder to the measured surface of the injection hole or the pre-stage. The average of three repeat measurements is used as the result of the tactile measurement. The diameter of the tactile sphere is 71 µm.

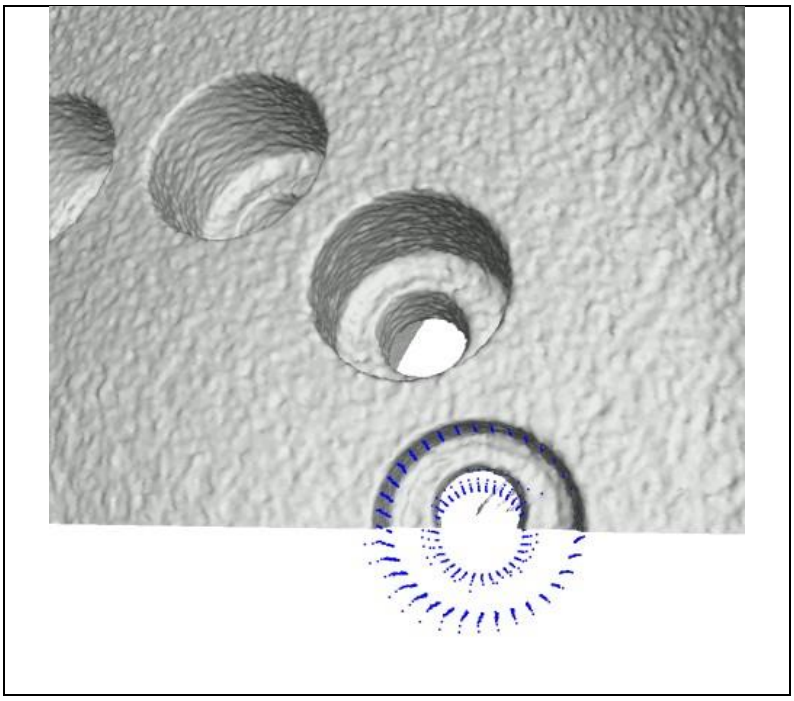


Figure 6: Results of tactile and CT measurements performed by PTB.

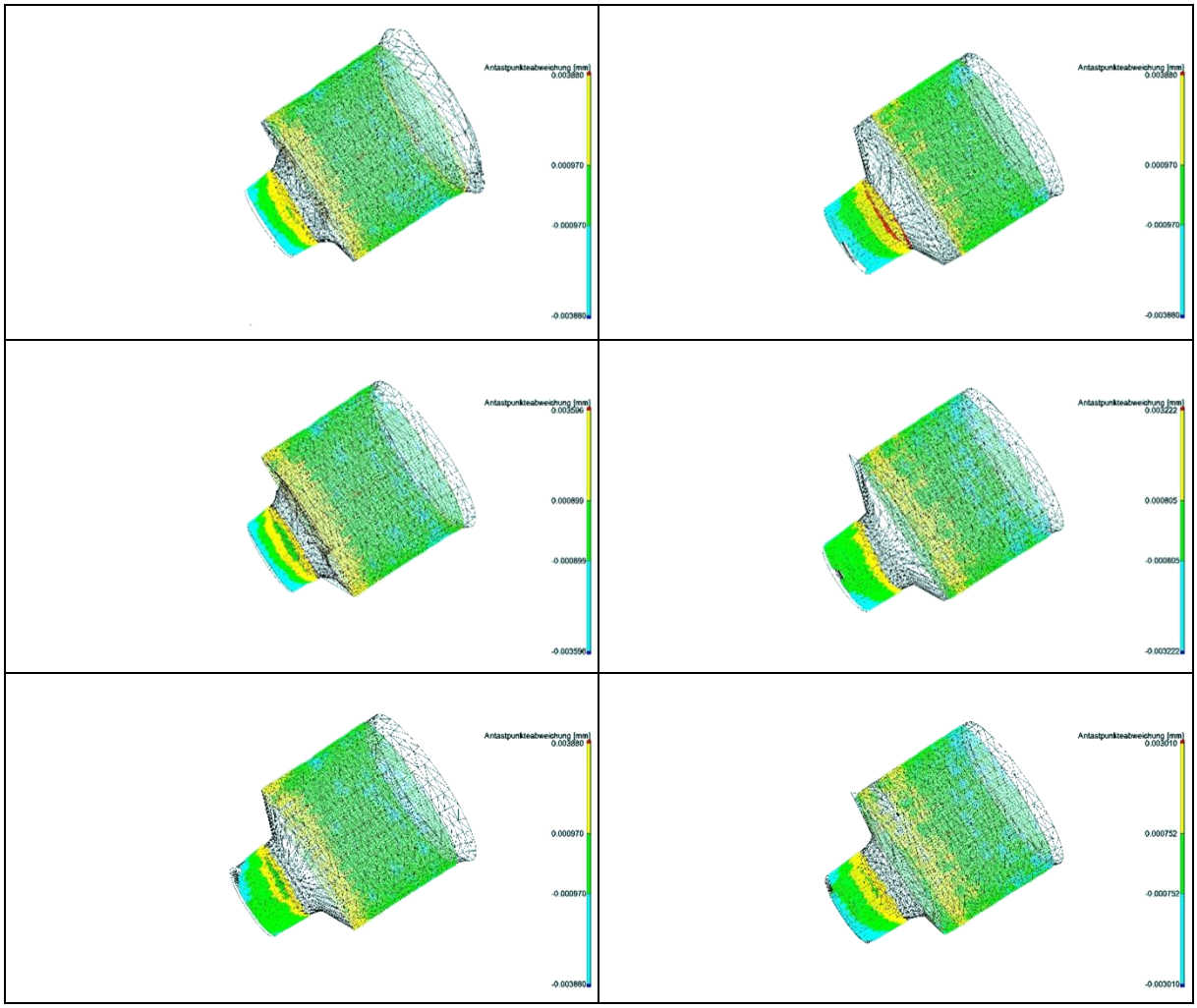


Figure 7: Meshes from tactile measurement with probing points used for cylinder fits with 3 repeat measurements each. Left: nozzle1, right: nozzle 6. Rounding and missing transition between injection hole and pre-stage lead to different lengths of the cylinder for the best-fit to the injection hole.

Table 1: Measured diameters of injection holes 1 and 6

injection hole 1	**tactile**	**CT**
mean radius of nozzle in µm	76.9	76.2
mean radius of pre-stage in µm	155.8	157.1
Cone angle of nozzle in °	5.54	3.66

injection hole 6	**tactile**	**CT**
mean radius of nozzle in µm	75.4	75.9
mean radius of pre-stage in µm	155.3	156.5
Cone angle of nozzle in °	3.23	3.2

A new beam hardening correction was applied to the above data set, based on a calibrated beam hardening curve. Corresponding projections are marked with the abbreviation "bh". This beam hardening correction replaces the NIKON level 2 correction (see Figure 8).

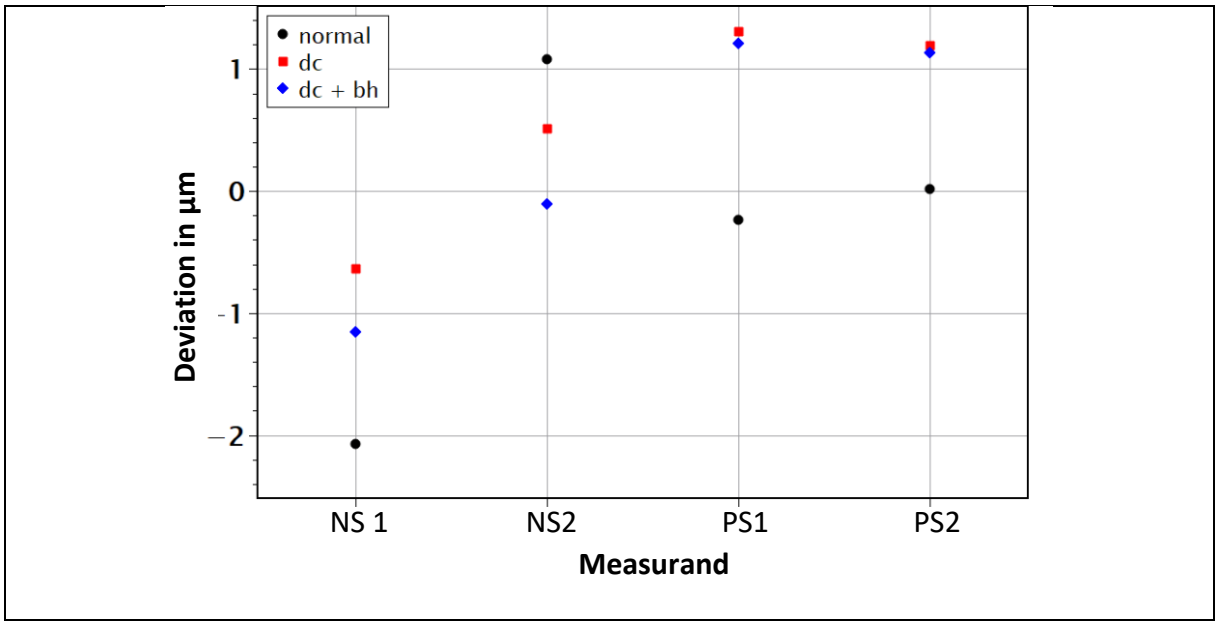


Figure 8: Graphical representation of the difference between tactile measurement and CT after various corrections. "normal" = standard workflow without own corrections. "dc" = above workflow. "dc + bh" = additionally with measured beam hardening. NS = nozzle, PS = pre-stage.

The inner radius of the nozzle is probably subject to greater uncertainty in the tactile measurement since different nozzle lengths are observed in the repeat measurements and the nozzle is conical. Thus, the results at the pre-stage are to be classified as the most reliable. Here, the results without additional corrections show the smallest deviations of -0.24 µm and 0.02 µm. After corrections, the deviations increase to 1.21 µm and 1.13 µm, whereby the additional beam hardening correction has only a marginal influence. However, surface roughness must also be taken into account in the evaluation. In the pre-stage, the roughness cannot be determined, so the roughness of the outer cylinder can serve as the only reference. If we transfer the above results and assume that the tactile measurement determines a surface 1.0 µm further outside than the CT, the CT results after correction deviate from the tactile results by only 0.23 µm and 0.13 µm. However, the influence of the roughness is probably smaller, since the diameter of the probe ball is smaller.

For the cone angles of the nozzles, a wide range of measured values in the tactile repeat measurements is noticeable. For nozzle 1, the minimum and maximum values are 3.3° apart for nozzle 6 1.9°.

2.2 Comparison tactile - CT measurement of Bosch

The nozzles 1 and 6 used in section 2.1 were also selected for comparison with the reference data provided by Bosch (see Figure 9). The mean diameters (cylinder fits) and the diameters in defined measuring planes were evaluated. The position of the measuring planes was taken from the reference data from Bosch.

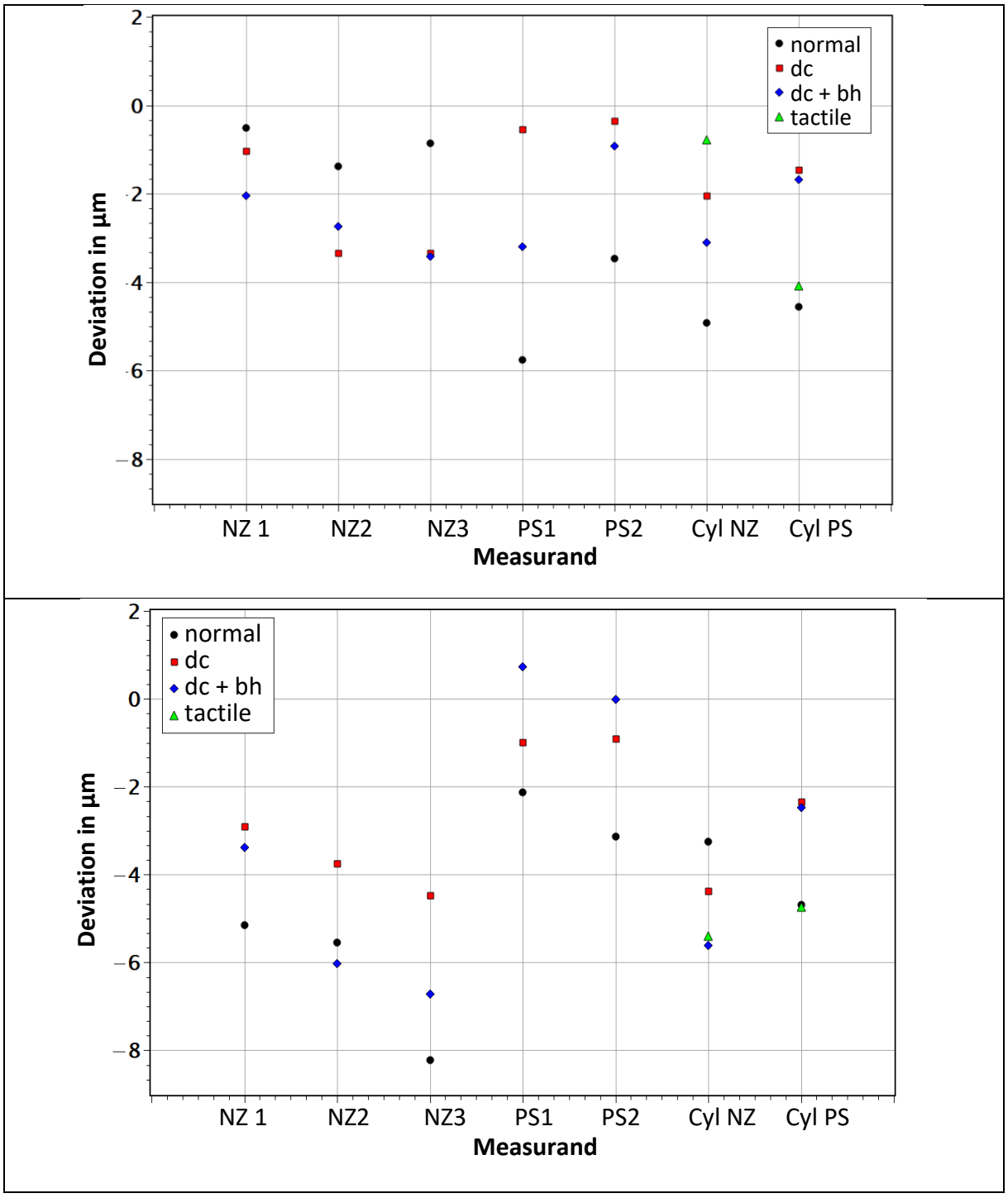


Figure 9: Comparison of the CT measurements carried out by Bosch and the tactile reference data. Inner diameters of nozzle 1 (top) and nozzle 6 (bottom). "Cyl" denotes the mean diameters, "NZ"= nozzle, "PS" = pre-stage, numbers denote measuring levels.

The comparison shows that larger diameters were systematically measured in the Bosch reference measurements.