Microgear Measurement Standards: Comparing Tactile, Optical and Computed Tomography Measurements

Stephan Jantzen, Martin Stein, Andreas Dietzel, and Karin Kniel

Introduction

Microgears are widely used in industry, as they are essential components of gearboxes used in precision engineering, medical technology, and robotics. In these industries, miniaturization is an ongoing goal, entailing fewer material costs, smaller sizes, and more efficient operation. However, the inspection during the production of microgears is *challenging* because the required measurement uncertainties are small, and because measuring the small workpieces requires special probes (Ref. 12).

The measurement technology used in this context faces the challenge of developing reliable measuring machines and established evaluation routines. However, microgear *measurement standards* are rare, even though adequate quality control of gears requires gear-like measurement standards. Therefore, the Physikalisch-Technische Bundesanstalt (PTB), Germany's national metrology institute, has developed two microgear measurement standards.

Measurement standards are a user-friendly instrument for checking and selecting adequate measurement technology (Ref. 2). Measurement standards benefit industry when substitution measurements are performed. Measuring calibrated workpieces allows systematic errors to be corrected that arise in measuring machines and task-specific measurement uncertainties to be estimated.

Comparison measurements are useful for evaluating the performance of laboratories, finding problems, confirming measurement uncertainty claims, and checking the performance characteristics of a given method (see ISO 17043).

In the following chapter, we will present PTB's two microgear measurement standards. Their analyses using seven measurement methods are then presented, evaluated and compared with each other.

Overview of the Two Involute Microgear Measurement Standards Developed at PTB

This section gives an overview of the two microgear measurement standards developed at PTB (internal and external microgear). In both workpieces, four gears are embedded (1 mm, 0.5 mm, 0.2 mm, and 0.1 mm modules); each gear has four teeth realized (Table 1). The wide range of modules suits different applications. Additionally, measuring the four modules may reveal size-dependent effects of the measuring machine used.

Both measurement standards were manufactured from carbide and titanium. Carbide yields better machinability and higher mechanical stability. Titanium features a small absorption coefficient, which allows computed tomography (CT) measurements to be performed. Both workpieces have a tip diameter of 20 mm, which facilitates handling and clamping.

External microgear measurement standard. The external microgear measurement standard consists of an upper datum reference, a gear disk, and a lower datum reference (Fig. 1) (Refs. 2, 13). These three parts are joined by pinning and gluing.

Internal microgear measurement standard. The most

Table 1 Properties of the two microgear measurement standards

	External microgear	Internal microgear
Facewidth	4 mm	2 mm
Outer diameter	22 mm	40 mm
Profile	Involute	
Normal modules mn	1 mm, 0.5 mm, 0.2 mm, and 0.1 mm	
Teeth realized per module	4	
Pressure angle a.	20°	
Tip diameter	20 mm	
Helix angle #	0°	
Profile shift coefficient x	0	
Material	Carbide and titanium	
Machine process of the profiles	Wire electric discharge machining (Wire EDM)	
Calibrated features	Profile and helix	

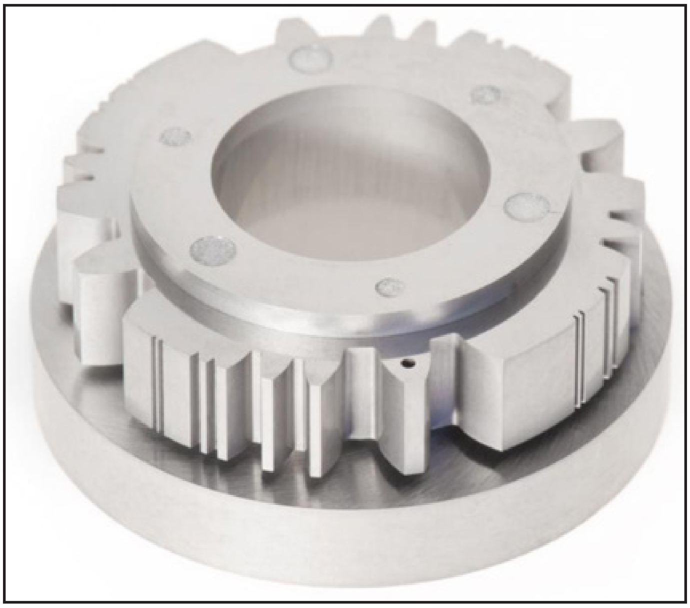


Figure 1 External microgear measurement standard. The bore hole denotes Tooth 1. The inner bore reduces the length to be penetrated by X-ray when measuring with the CT system.

prominent characteristics of the internal microgear measurement standard are its facewidth of 2 mm and its custom clamp (Fig. 2) (Ref. 6). The clamping can be loosened, which allows the gear disk to be measured separately from the clamp (for example, for CT or optical measurements). Furthermore, the design allows the workpiece to be measured in a flipped state. The facewidth of 2 mm matches the shaft length of the tactile probe in the µCMM used for calibration. Accordingly, the µCMM can characterize the whole flank for calibration.

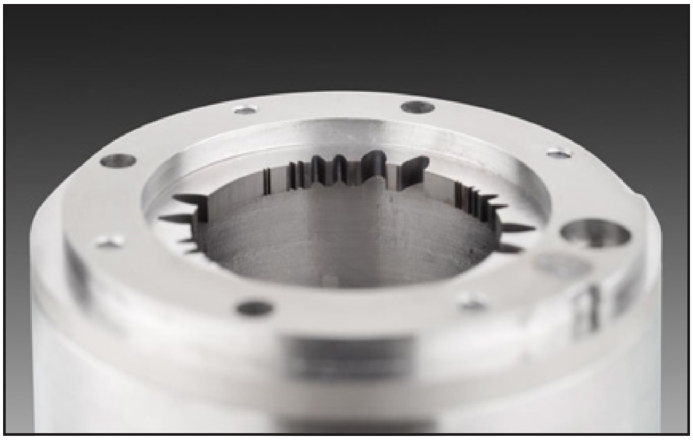


Figure 2 Internal microgear measurement standard with custom clamp.

Comparison Measurements

The comparison measurements featured seven measurement methods (see Table 2). The following sections give details of the different measurement parameters.

Tactile calibration on a µCMM. The calibration measurements were performed on the Zeiss *F25* micro coordinate measuring machine (µCMM). The µCMM calibrated both measurement standards with measurement uncertainties in the sub-micrometer range (Table 3). The probing force was 1 mN.

The tactile calibration provided the reference values for the comparison measurements. The calibration values refer to the deviations of the profile and the helix (see ISO 1328 and ANSI/AGMA 1012-G05). The calibrated gear parameters were evaluated in the software of the measuring machine (Zeiss *Gear Pro* (Ref. 8).

The smallest module embodied (m_n = 0.1 mm) was not calibrated because the probing element, whose sphere diameter is 125 µm, is too large for the tooth spaces. Figure 3 shows the measurement setups.

Table 2 Overview of measurement methods we compared (the abbreviation GMI stands for gear measuring instrument)

	Measurement of external microgear	Measurement of internal microgear
Tactile calibration on a µCMM	Except 0.1-mm module	Except 0.1-mm module
Tactile measurement on a GMI with standard probe	Except 0.1-mm module	Except 0.1-mm module
Tactile measurement on a GMI with custom microprobe	Yes	Not yet
Computed tomography (CT) measurement	Yes	Yes
Optical measurement: focus variation	Yes	Yes
Optical measurement: transmitted light	Not possible	Yes
Tactile-optical measurement	Yes	Not yet

Table 3 Measurement uncertainties of the tactile calibrations. The measurement uncertainties are equal for all three modules (1 mm, 0.5 mm, and 0.2 mm)

Parameter	Internal microgear, titanium U_{cal} (k=2) in µm	Internal microgear, carbide U_{cal} (k=2) in µm	External microgear, titanium and carbide U_{cal} (k=2) in µm
Profile slope deviation $f_{H\alpha}$	0.6	0.5	0.4
Profile form deviation $f_{f\alpha}$	0.5	0.5	0.3
Total profile deviation F_α	0.7	0.6	0.5
Helix slope deviation $f_{H\beta}$	0.5	0.4	0.4
Helix form deviation $f_{f\beta}$	0.5	0.5	0.3
Total helix deviation F_β	0.6	0.6	0.5

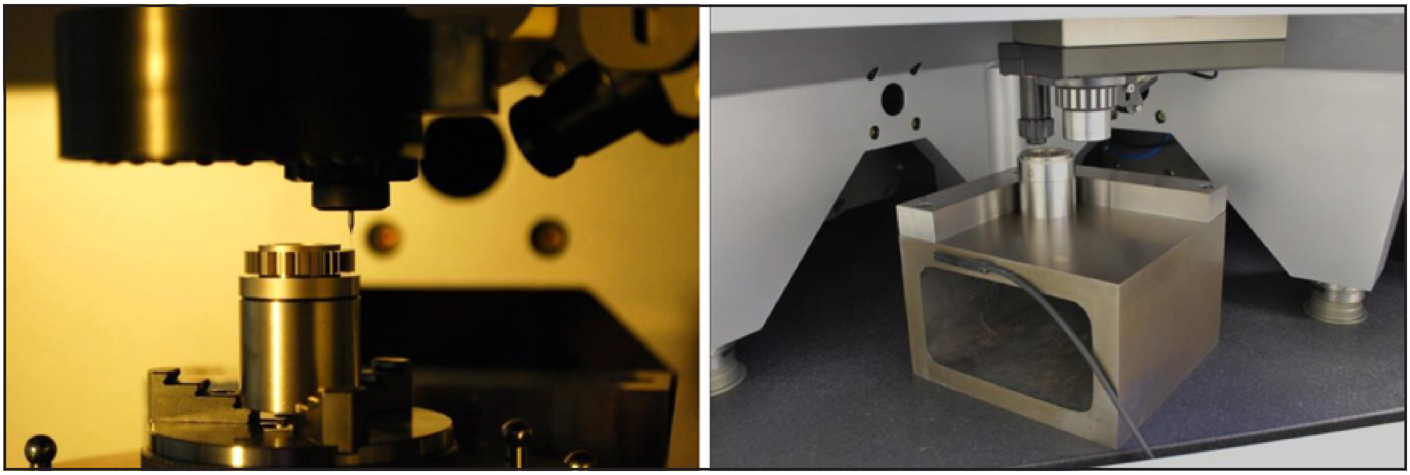


Figure 3 Measurement setups of the microgear measurement standards on the µCMM. The left side of the figure shows the external measurement standard (Ref. 2)]. The right side of the figure shows the internal measurement standard and its custom clamp.

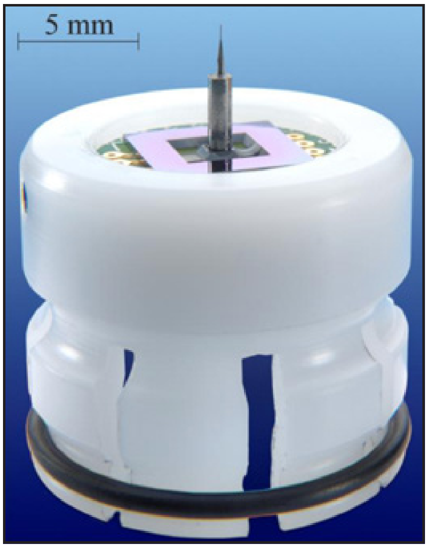


Figure 4 Detailed view of the IMT/PTB microprobe with sphere diameters down to 50 µm. The microprobe is integrated into our GMI.

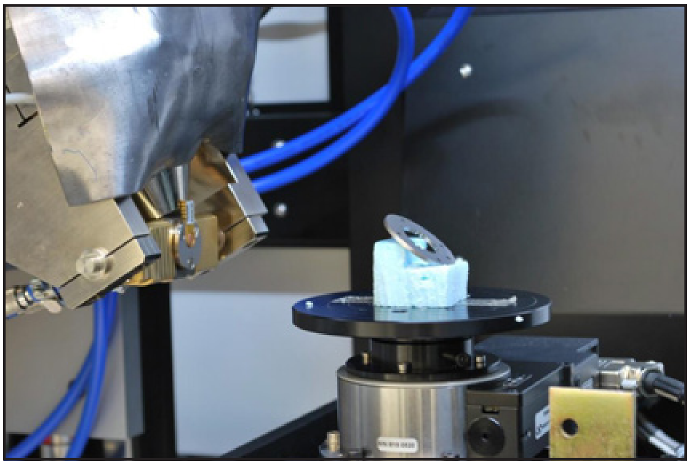


Figure 5 Measurement setup of the CT system. The X-ray source can be seen on the left-hand side of the image above. The measurement standard, positioned on the rotary table, can be seen on the right. The detector is situated on the far-right side and is not depicted in the image above.

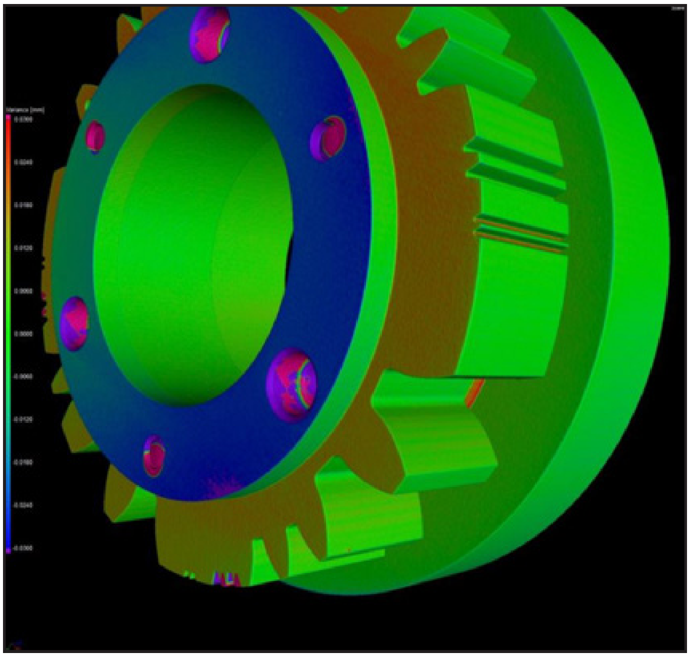


Figure 6 Target/actual comparison of the CT measurement regarding the CAD model.

Tactile measurements on a gear measuring instrument (GMI). Gear measuring instruments (GMIs) feature a rotary table for measuring cylindrical workpieces. On our Klingelnberg *P40* GMI, we used two different probes: a conventional probe with a 300-micrometer ruby sphere and a custom microprobe with a monolithic shaft and 100-micrometer sphere (Fig. 4). This microprobe was developed by TU Braunschweig and PTB (Refs. 1, 10). The probing force was between 15 mN (with the microprobe) and 825 mN (with the standard probe).

Computed tomography (CT) measurements. The CT measurements were performed on a Nikon *MCT 225* (cone-beam CT). This measurement method can check internal dimensions and "combine dimensional quality control with material quality control in one single quality inspection run" (Ref. 7).

The measurement standards were tilted 45° for measurement (Fig. 5). The CT measurement of the internal microgear used an invar foil with accurately known dimensions as the reference object (Ref. 3). The invar foil was measured before and after the microgear measurement standards were measured. Comparing the CT results of the invar foil with the reference value from the tactile calibration yielded a scaling factor that was applied to the measurement results of the microgear. Evaluations of CT measurements may include:

- Comparison with the CAD model (see Figure 6)
- Areal evaluation
- Conventional, line-based evaluation

For comparison with the line-based tactile calibration, we extract line features from the volumetric CT data.

The CT measurement generates a file containing the spatial coordinates of every measurement point. For this reason, the *gear* parameter analysis required additional software to separate points and to extract ine elements (profile lines and helix lines, see also Figure 12). In this study, we used a line-based evaluation for comparison (see ISO 1328).

Table 4 compares the CT measurement parameters of the external and internal microgears.

For CT measurements, the overall size of the workpiece determines the largest magnification that can be achieved. The internal microgear measurement standard has an outer diameter of 40 mm, whereas the external microgear measurement standard has an outer diameter of 22 mm. This explains the difference in the resulting voxel sizes: $(22.7\,\mu m)^3$ voxel size for the internal microgear, compared to $(17.5\,\mu m)^3$ voxel size for the

Table 4 Overview of the CT measurement parameters of the external and internal microgears

		External microgear	Internal microgear
Measuring data	Voltage	185 kV	190 kV
	Power	12.4W	17.5 W
	Pre-filter	0.8 mm Cu	1 mm Cu
	Measuring time	120 min	167 min
	Projections	1800	2500
	Magnification	12.9×	8.8×
	Resolution detector	2048×2048 pixels	
	Exposure time	2×2.8 s	4 s
	Voxel size	$(17.5\,\mu m)^3$	$(22.7\,\mu m)^3$
Reconstruction	Beam hardening filter	2	2
	Reconstruction filter	2	2
	Median filter	3×3 pixel	No median applied

external microgear, which could have been further decreased by reducing the distance between the workpiece and X-ray source. However, algorithms of the CT software achieve sub-voxel resolution. Additional key parameters are the penetration length and the material permeability. Both parameters influence the X-ray power needed for the measurement, which itself influences noise in the measurement results. The maximum penetration length of the external gear is ~12 mm and ~20 mm for the internal microgear. Thus, measuring the internal microgear yielded more *noise*. As a result, the form deviations measured by CT are on average *twice as high as the calibration values*. Furthermore, the limited resolution of the CT measurements (mainly due to the large voxel size) leads to rounded edges. Thus, the gear parameter analysis shows negative profile slope deviations (tip relief).

The data generated by means of a CT measurement are several gigabytes depending on the detector resolution and on the number of projections.

Optical measurements. We used two optical measurement methods: a focus variation method and a transmitted light method (Fig. 7).

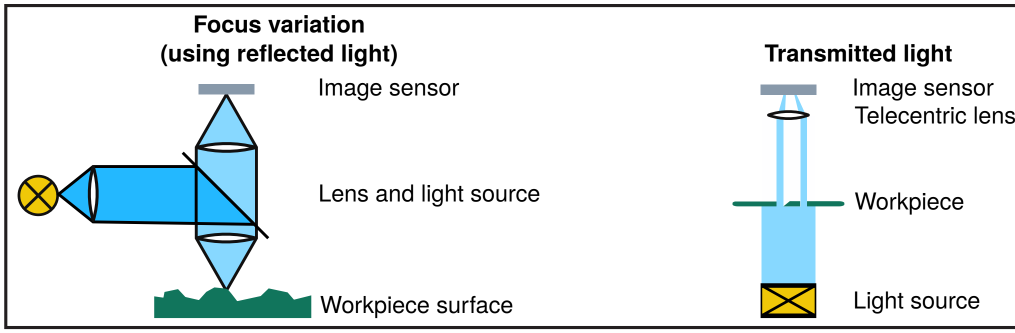


Figure 7 Simplified visualization of the two optical measurement principles.

Focus variation method. The focus variation measurements were performed on an Alicona InifiniteFocus G4 (external microgear) and InfiniteFocus G5 (internal microgear). The workpiece was clamped at a 45° angle (between the optical axis and the gear axis, Fig. 8) with the Rotation Unit.

Figure 8 Measurement setup of the Alicona InifiniteFocus. The measuring machine allows roughness measurements and 3-D measurements to be performed.

We used two lenses featuring different magnifications and, thus, different resolutions (see Table 5).

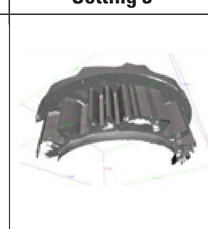
Table 5 Specifications of lenses used for focus variation

	5× lens	10× lens
Image area	2.9 mm × 1.4 mm	2.2 mm × 1.1 mm
Numerical aperture	0.15	0.3
Maximum resolution (lateral)	2.2 µm	1.1 µm
Resolution (vertical)*	0.4 µm–8.36 µm	0.1 µm–2 µm

* The vertical resolution depends on the scanning speed

We tested four different settings for the external microgear measurement standard. The 3-D view obtained with Setting 1 showed several measuring artifacts that may be caused by sub-optimal exposure time and reflections. Setting 4 showed the best results due to the high magnification. However, the 0.1 mm module could not be evaluated because too many artifacts were on the teeth. Moreover, the focus variation measurements took a long time to perform (Table 6). However, the measurement time could have been reduced by optimizing the settings, as we did with the Alicona InfiniteFocus G5 and the internal microgear.

Table 6 Overview of measurements performed using the Alicona InifiniteFocus G4

	Setting 1	Setting 2	Setting 3*	Setting 4
3D view				
Measuring time	24h	400h	20h	50 h
Resolution (lateral)	7.8 µm	7.8 µm	3.9 µm	3.9 µm
Resolution (vertical)	0.25 µm	0.25 µm	0.25 µm	0.25 µm
Exposure time	80 ms	automatic	40 ms	20 ms
Magnification	5×	5×	10×	10×
Polarization	Active	Active	Active	Active

* Not a full measurement

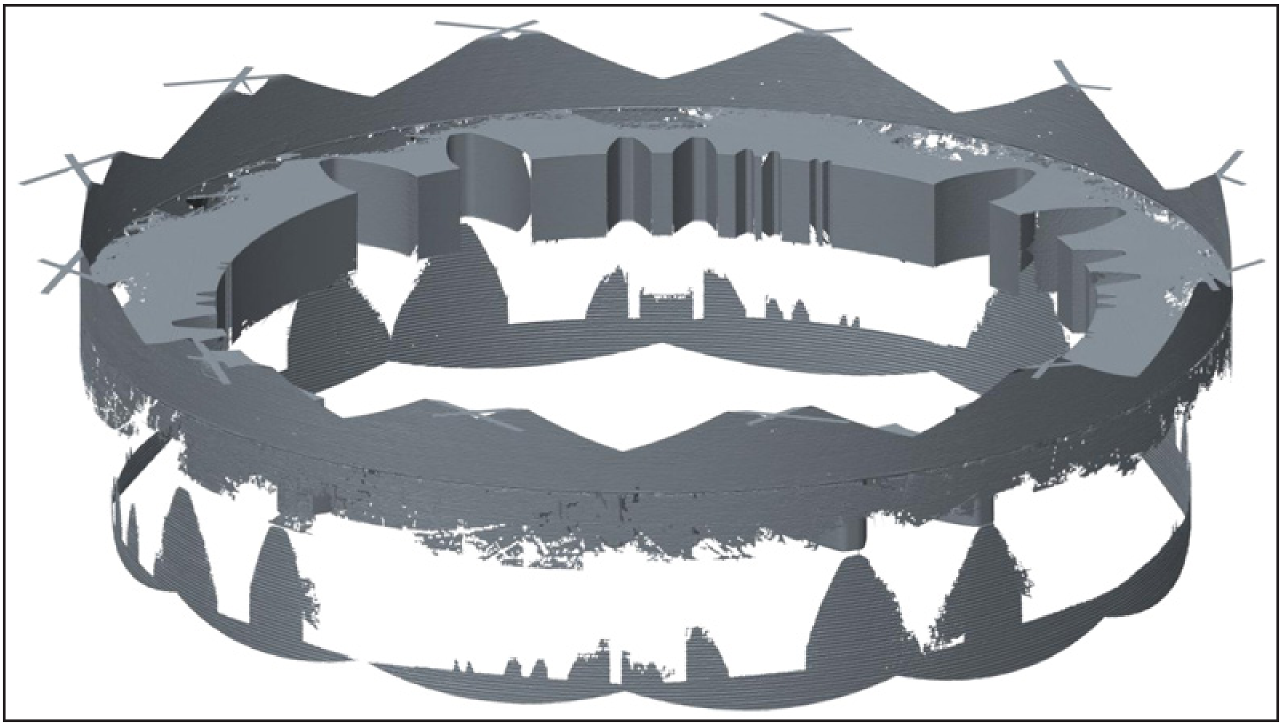


Figure 9 Reconstruction of the internal microgear measurement standard with focus variation.

On the InfiniteFocus G5, what worked best for the internal microgear was 10× magnification, no polarizer, 0.15 seconds exposure time, 8.5 µm lateral resolution, and 0.35 µm vertical resolution. The measuring time was 106 minutes. It was not possible to capture the whole measurement standard, but all gear teeth (Fig. 9). Thus, we had to change the definition of the workpiece coordinate system for evaluations of this measurement. Nearly every tooth space shows small artifacts, but they mainly occurred at the edges, which did not impair the *traditional* line-based evaluation.

Transmitted light method. The optical transmitted light measurements were limited to the *internal* microgear. It was not possible to measure the external microgear because the lower datum reference diameter is larger than the tip diameter. Therefore, the lower datum reference would have blocked the light (Fig. 1).

The measuring machine used was a Werth Videocheck UA. As shown in Figure 7, the transmitted light method yields 2-D point data (*x*- and *y*-coordinates). Thus, it was only possible to analyze profile lines (without helices). Additionally, the imaged profile lines are an *envelope* of the whole facewidth, which leads to systematic errors. Accordingly, this measurement method is commonly used to characterize thin or 2.5-dimensional objects. The systematic error when measuring gear profiles depends on the:

- Helix deviations
- Twist (Ref. 15)

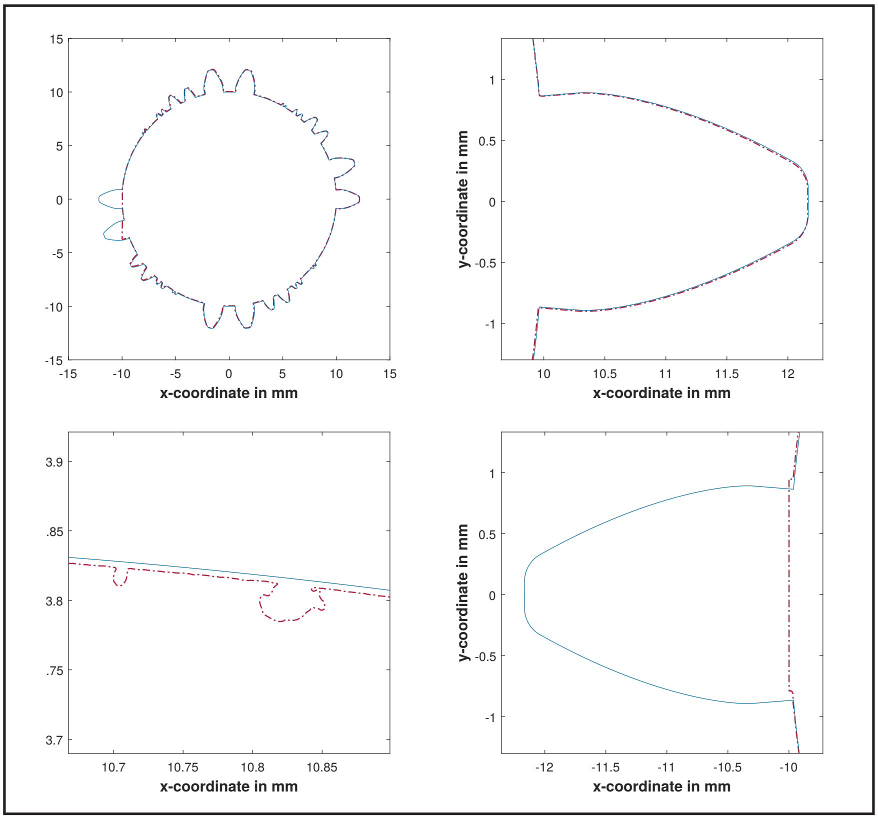


Figure 10 Visual analysis of the transmitted light measurement. In all the above figures, the red dashed and dotted line represents the measurement and the blue solid line represents the contour of the CAD model, which is the target geometry. Upper-left plot: overview of the measured inner contour of the microgear. Upper-right plot: Detailed view of a tooth with a 1 mm module showing good agreement with the CAD model. Lower-left plot: Detailed view of two particles on the tooth surface (information on their z-coordinate cannot be provided using this measurement method). Lower-right plot: Here, the automatic edge detection has failed and skipped the tooth.

- Alignment of measurement standard and measuring machine
- Contamination

When measuring with transmitted light, every particle on the tooth surface alters the measurement result (Fig. 10, lower-left plot). By contrast, it is unlikely that these particles would alter the *tactile* measurement result; either the particles are not positioned on the scanned line or the tactile probe would push away loosely adhering particles.

The measurement program was created by means of automatic edge detection. Here, the software requires only a starting position with the optics focused on the inner contour and does not require information on the real gear geometry. However, using this algorithm led to teeth being skipped (Fig. 10, lower-right plot).

Tactile-optical measurement. The tactile-optical measurements were performed on the multi-sensor CMM Werth Videocheck UA quipped with the fiber probe developed at PTB (Fig. 11) (Ref. 11). Probing forces were as low as 1 µN.

Comparison and discussion of the measurement results. In summary, the two workpieces were characterized by seven measurement systems. For comparison purposes, we focused on the deviations of the gear parameters from the calibration values, the measuring time, and the measurability of the smallest module (Table 7).

Tactile measurements are the most established approach in gear metrology. Thus, the standard-compliant evaluation of the deviations (see ISO 1328) is based on line elements, which are the output of tactile measurements (instead of surface data). The high level of development of such elements makes tactile measuring machines favorable.

To ensure comparability of the measurement results obtained by means of the different principles, it was necessary to process the data and extract the line-based features of the standard evaluation (Fig. 12).

The focus variation method relies on light reflections of the

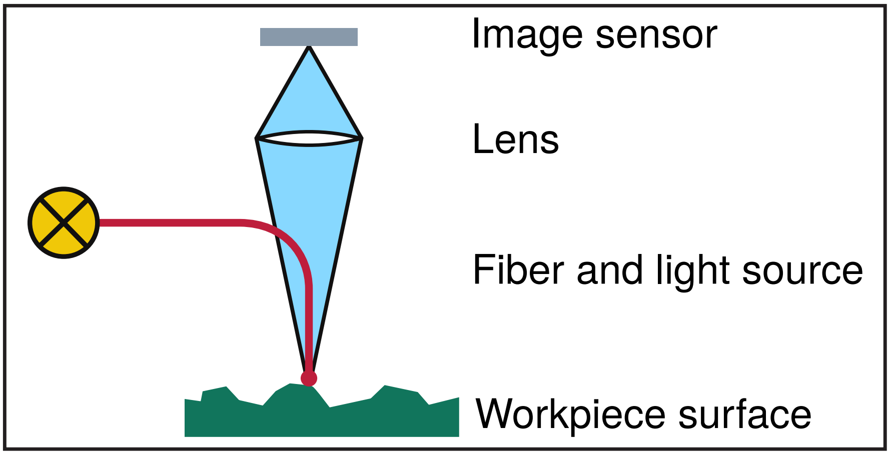


Figure 11 Working principle of the fiber probe. The light merges into the fiber (depicted in red) and the image sensor detects deflections of the fused sphere at the tip of the fiber.

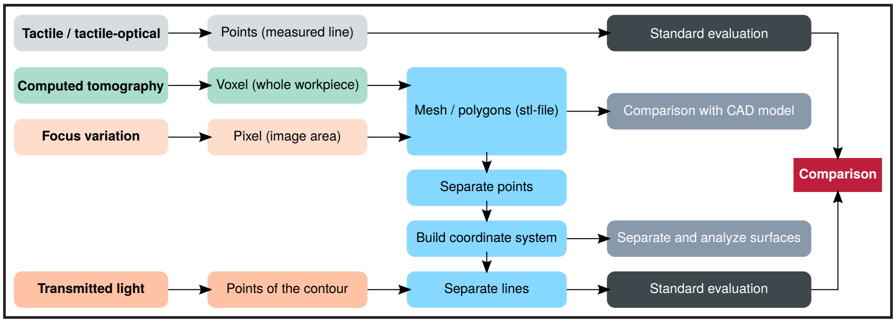


Figure 12 Process flow of the evaluation in the comparison measurements. Standard evaluation refers to the ISO 1328-1.

Table 7 Comparison of measurement parameters

Measurement method	Measuring machine	Measurement time	Parameters
Tactile (CMM)	Zeiss *F25*	2 min per tooth for scanning, up to 10 min for single-point probing	**Gear parameter evaluation:** Zeiss Gear Pro **Sphere diameter:** 125 µm **Strategy:** Scanning (single-point probing used additionally for the external microgear)
Tactile (GMI with standard probe and custom microprobe)	Klingelnberg *P40*	2 min per tooth	**Gear parameter evaluation:** Klingelnberg software **Sphere diameter:** 300 µm (standard probe), 50 µm and 300 µm (custom microprobe of PTB and TU Braunschweig) **Strategy:** Scanning
Computed tomography (CT)	Nikon *MCT 225*	120 min per workpiece	**Voxel size** (depending on the workpiece size): $(17.5\ \mu m)^3$ for the external gear, $(22.5\ \mu m)^3$ for the internal gear **Gear parameter evaluation:** Hexagon 3D Reshaper and Gear, evaluation takes up to **five hours per tooth to perform** (400 points per millimeter, 1 mm module)
Optical (focus variation)	Alicona *InifiniteFocus G5*	106 min per workpiece	**Lenses:** 5× and 10× **Gear parameter evaluation:** Hexagon 3D Reshaper and Gear, evaluation takes up to **five hours per tooth to perform** (400 points per millimeter, 1 mm module). There is an additional software module from Alicona for gears, which might reduce evaluation time
Optical (transmitted light)	Werth Videocheck *UA*	1 min per tooth	**Gear parameter evaluation:** Zeiss Involute Pro **Lens:** 10×
Tactile-optical measurement	Werth Videocheck *UA*	5 min per tooth	**Gear parameter evaluation:** WinWerth with gear module **Sphere diameter:** 125 µm **Strategy:** Single-point probing

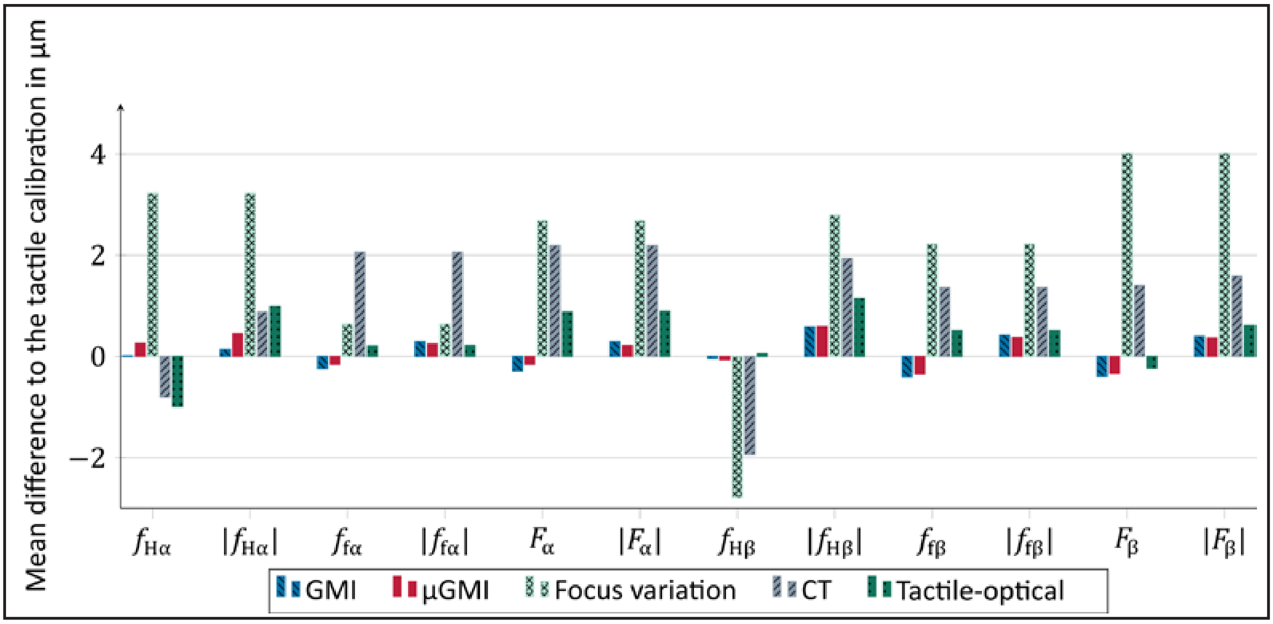


Figure 13 Comparison measurements of the external microgear measurement standard.

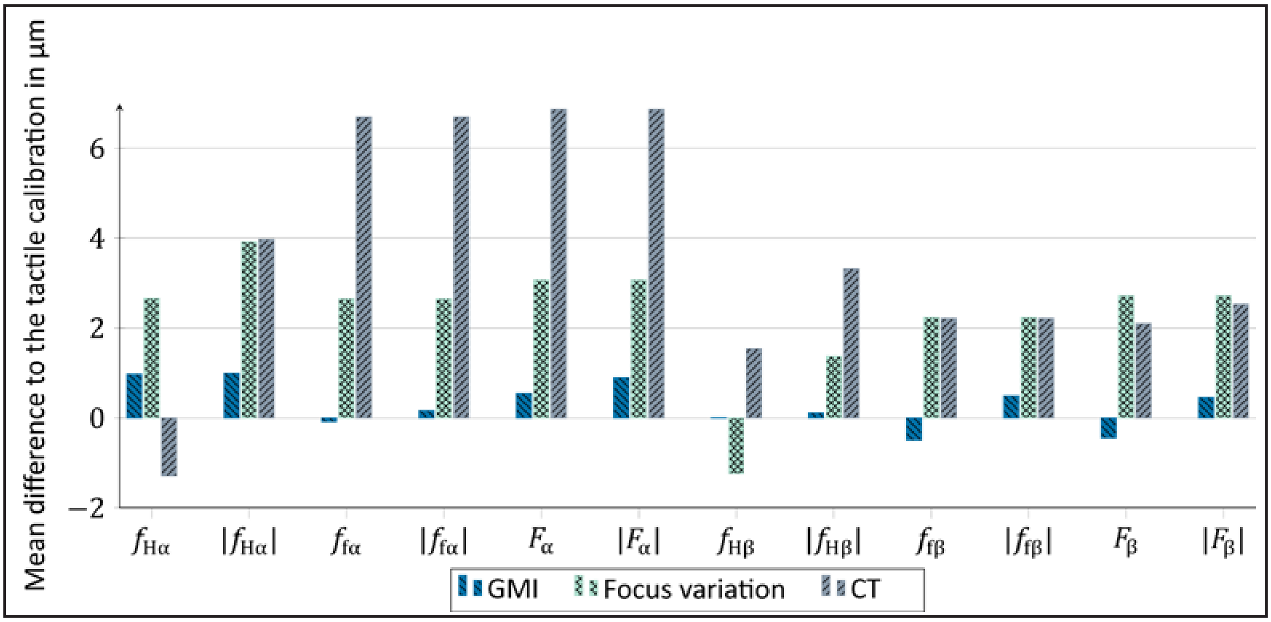


Figure 14 Comparison measurements of the internal microgear measurement standard.

Table 8 Evaluation of the measurement methods regarding microgear metrology		
Measurement method	Advantages	Disadvantages
Tactile (µCMM and GMI)	Fast, accurate, easily traceable	Line-based characterization of the workpiece, special probes required, sphere diameter must match the tooth spaces, most probes are fragile, probing may alter the workpiece due to high Hertzian stress
Computed tomography (CT)	Fast measurement, volumetric characterization of the workpiece, contactless, can check internal dimensions, measurement of very small modules, unaffected by contamination of the workpiece	Differences of several micrometer from the calibration values, resolution depends on the overall size of the workpiece and length to be penetrated by the X-rays, calibrated reference object needed to achieve highest available accuracy (scale correction), strong noise, data analysis requires considerable processing power and time
Optical (focus variation)	Fast areal characterization of the workpiece, contactless	Differences of several micrometer from the calibration values, occasional artifacts, sensitive to contamination, measurability depends on surface finish and on the angle between workpiece surface and optical axis, data analysis requires considerable processing power and time
Optical (transmitted light)	Fast, contactless, information on the target geometry is unnecessary due to the edge detection	Systematic errors due to the measurement principle (only 2D data, compared to 3D data from all other measurement methods, envelope contour from all z-coordinates), sensitive to contamination, line-based characterization of the workpiece
Tactile-optical	Lowest probing force (1 pN), smallest probe spheres available (40 µm) [14]	Line-based characterization of the workpiece, sticking effects due to the small stiffness of the fiber, measurability depends on surface finish

workpiece surface onto the image sensor. In this study, measuring gears required that the workpieces be tilted to ensure an adequate angle. Furthermore, the fixed focal length of the lenses limits the reconstruction internal gears — in the case of the internal microgear measurement standard, we were not able to completely reconstruct the workpiece.

CT systems allow contactless measurements that yield a complete 3D representation of the workpiece. However, the resolution depends on the workpiece size (in contrast to all other methods described in this work). Accordingly, CT measurements yield low resolutions for gears whose ratios of the outer diameter to the module are high.

The following two figures show the measurement results. Measurement results of the 1 mm, 0.5 mm, and 0.2 mm modules are stated in mean differences to the tactile calibration (regarding all modules and teeth). First, we computed the single differences (measurement result minus the corresponding result of the calibration). Afterwards, we computed the mean of these differences for every gear parameter ($f_{H\alpha}$, $f_{f\alpha}$, F_α, $f_{H\beta}$, $f_{f\beta}$, F_β) because the differences between the modules are mostly negligible, whereas the differences regarding the gear parameters are decisive. The term "abs" in the following figures states that the mean was computed using the absolute value of each difference.

The best agreement with the calibration values comes from *GMI* and µ*GMI*. Most of the Focus Variation and *CT* results differ markedly from the calibration values.

Analyzing the CT measurements of the internal microgear, we found out that the reason for the large differences in the profile form deviations is the virtual tip relief due to limited structural resolution. Shortening the evaluation range of the profiles at the tip end would have halved the differences to the calibration values.

In general, the form deviations of the CT and focus variation measurements are large due to limited resolution and noise — applying filters could decrease the differences to the calibration values. The comparison measurements using the GMI were successful because the results are within the measurement uncertainties.

Based on this study, we checked the applicability of the measurement methods used regarding microgear measurements (Table 8). The results show that each measurement method has shortcomings.

For industrial measurements, the combination of measurement time, cost, and quality can be a helpful key value to evaluate measurement methods. In the context of measurement technology, "quality" can be, among other things, influenced by accuracy, precision, measurement uncertainty, holistic characterization of the workpiece (3-D-reconstruction of the workpiece), robustness, and reliability. In terms of quality, the tactile measurements featured the smallest measurement uncertainties but generated only line data. CT measurements generated a holistic digital representation of the workpiece. The focus variation method was the most cost- and time-efficient measurement method. High-precision coordinate measuring machines and CT systems cost about two to five times as much as most optical systems.

Conclusion and Outlook

PTB successfully conducted comparison measurements of two microgear measurement standards using seven measurement methods. The following goals were pursued:

- Verification of the measurement standards and their calibration
- Performance evaluation of the measuring machines involved *regarding microgear measurements*
- Comparison of the measuring machines *based on actual measurement data*

Since a reasonable number of measurement results are within the measurement uncertainty of the calibration, we infer that the measurement standards are adequate and that their calibration is correct.

Industry and research may benefit from the workpiece-like measurement standards by testing and evaluating measuring techniques and machines. Using different techniques and machines to measure a calibrated workpiece reveals their individual advantages and disadvantages.

Small and medium-sized enterprises (SMEs) could take advantage of the comparison measurements by using the independent and comparable measurement data provided here. This will allow SMEs to have increased confidence when investing in measuring machines.

Ultimately, only some of the measurement methods were adequate for measuring the 0.1 mm module, namely: tactile measurement with the IMT/PTB microprobe, CT, optical measurements, and tactile-optical measurement with the fiber probe.

Currently, PTB and TU Braunschweig are further developing the custom microprobe (Ref. 9). Our goal is to expand the measurement capabilities of conventional GMIs and CMMs by integrating our microprobe. This allows the use of smaller probing sphere diameters and yields higher sensitivity. The microprobe is supplemented by a *microenvironment*, which is a portable separative device that protects and monitors the direct measurement environment and includes clamping and cleaning solutions (Refs. 4–5).

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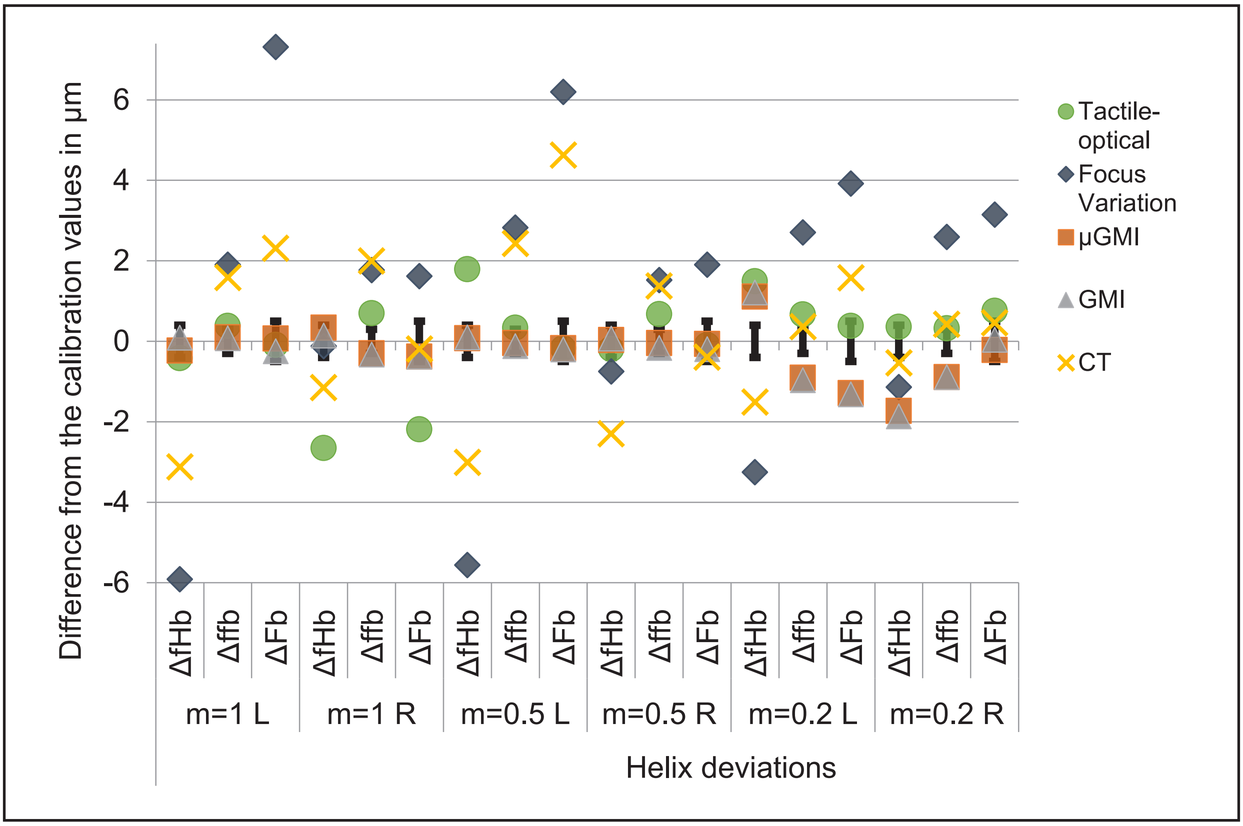

Figure 15 **Comparing the helix deviations for the modules from 0.2 mm to 1 mm of the external microgear. µGMI means a measurement using a custom microprobe integrated into our GMI. The best agreement with the calibration values comes from GMI and µGMI. Most of the Focus Variation and CT results differ markedly from the calibration values.**

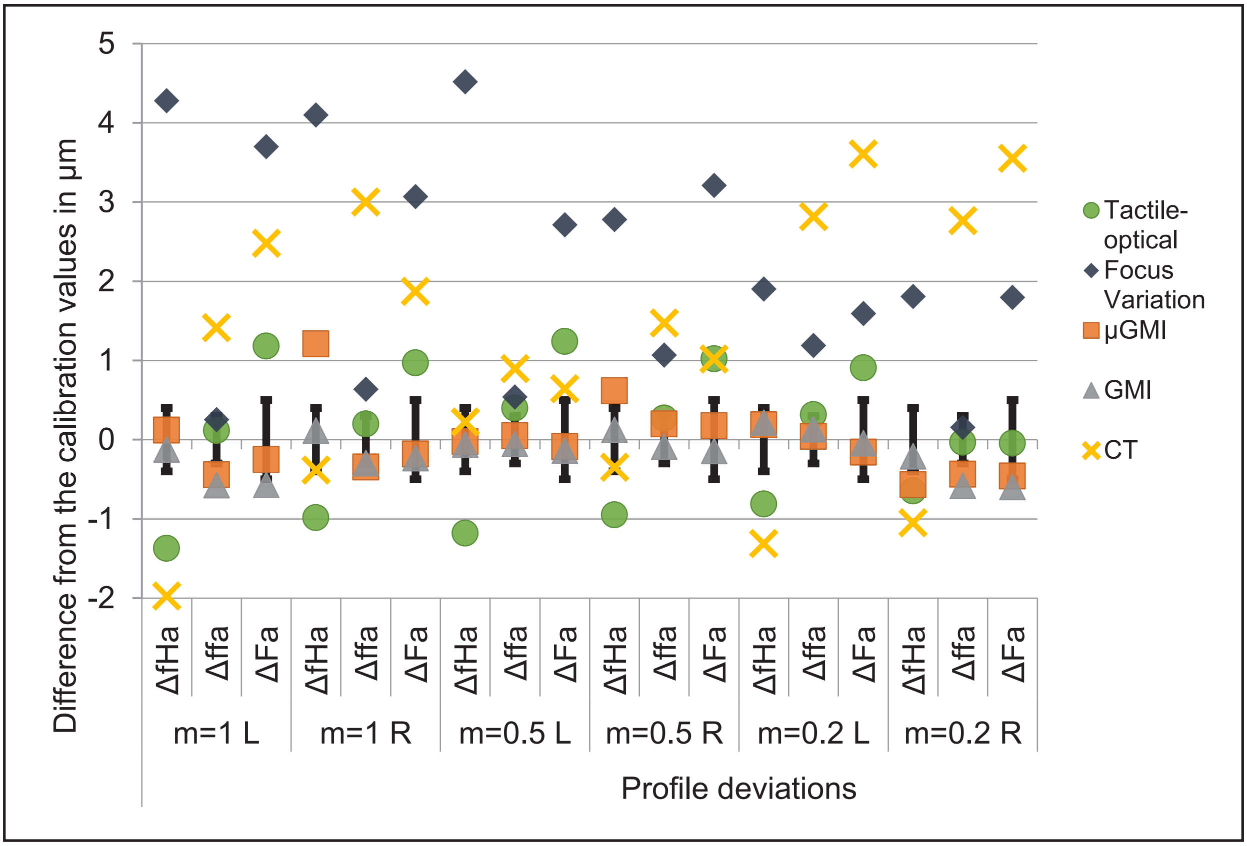

Figure 16 Comparing the profile deviations for the modules from 0.2 mm to 1 mm of the external microgear. µGMI means a measurement using a custom microprobe integrated into our GMI. The best agreement with the calibration values comes from GMI and µGMI. Most of the Tactile-optical and CT results differ markedly from the calibration values. The largest differences can be found in the Focus Variation measurements, which are consistently too large.

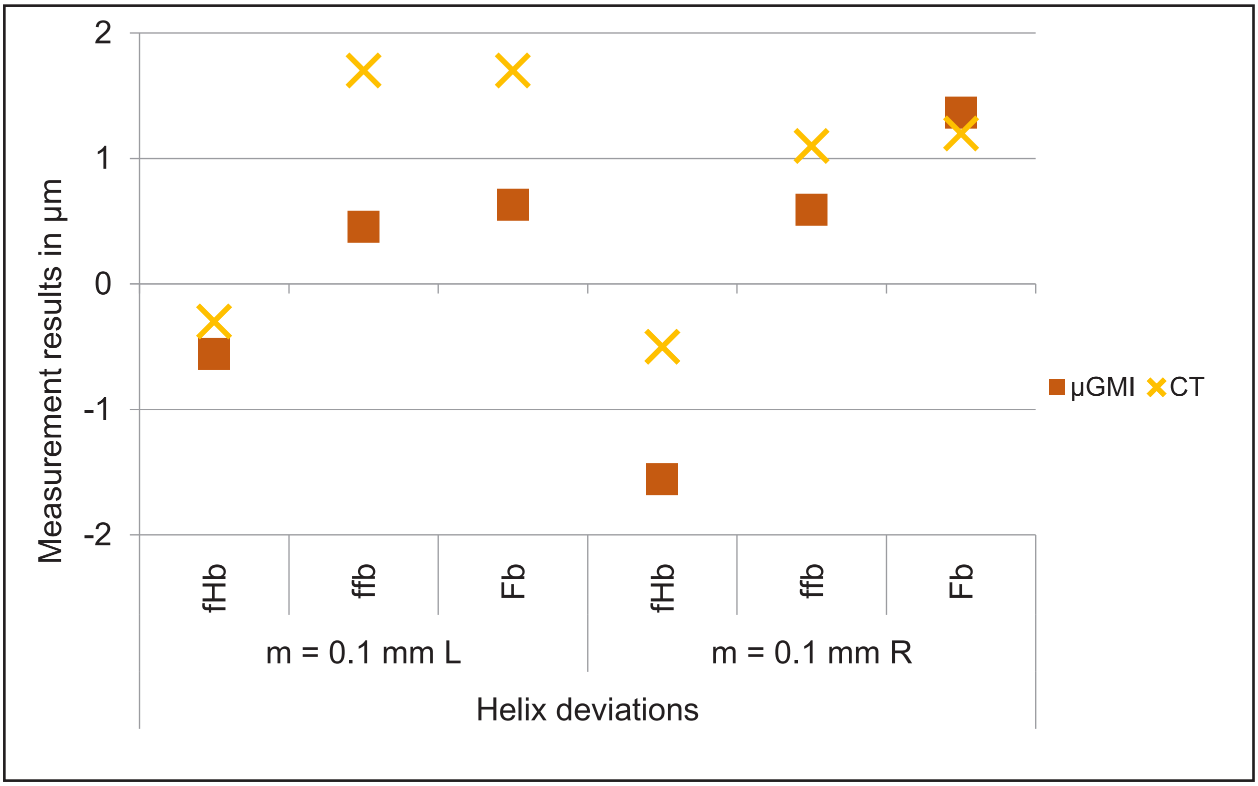

Figure 17 Comparing the helix deviations for the 0.1 mm module of the external microgear (CT and tactile measurement with custom microprobe on the GMI). Overall, the results agree.

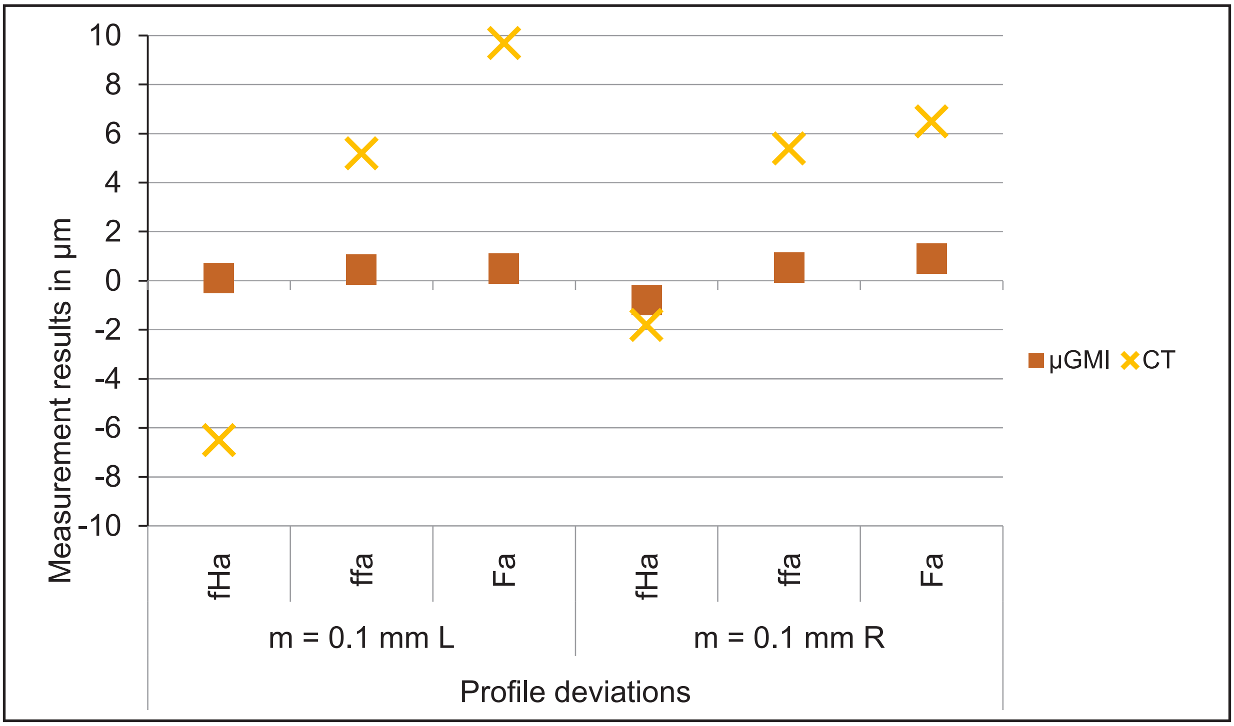

Figure 18 **Comparing the profile deviations for the 0.1 mm module of the external microgear (CT and tactile measurement with custom microprobe on the GMI). The length of the profile is short, which might explain the large deviations of the CT measurement.**

Supplemental Material

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For more information.
Questions or comments regarding this paper? Contact Martin Stein at *martin.stein@ptb.de*.

Stephan Jantzen received his bachelor and master's degrees in engineering science with a specialization in mechatronics from the Technische Universität Berlin in 2013 and 2015. Since 2016, he has been a research associate at the Physikalisch-Technische Bundesanstalt in the department Coordinate Metrology. In 2019, Jantzen finished his PhD thesis—"Design of a High-Precision Microgear Metrology System"—at the Institute of Microtechnology of Technische Universität Braunschweig.

Martin Stein studied mathematics and physics at Leibniz University Hanover and finished his PhD in 2012. He has since 2014 been the head of the working group for gear and thread metrology at the Physikalisch-Technische Bundesanstalt in Braunschweig, Germany. Stein is an active member in national standardization bodies for gear metrology of the VDI/VDE and DIN.

Karin Kniel studied mechanical engineering at TU Braunschweig. She has been employed in the Physikalisch-Technische Bundesanstalt for nearly 20 years. In 2007, she finished her PhD and became the head of the working group Gears and Threads. Since 2014, she has been the head of the Coordinate Metrology department. The task of this department is an industry-oriented dissemination of the SI-unit "meter" in the field of dimensional 3-D metrology. With the goal of ensuring traceability and enhancing accuracy, Kniel's department develops measurement methods, facilities and standards.

Andreas Dietzel received his diploma and PhD degrees in physics from the University of Göttingen (Germany) in 1986 and 1990. From 1990 to 1994, he worked in the IBM Laboratory of Surface and Structure Analysis in Boeblingen (Germany), and from 1994 to 1996 at the IBM Research Laboratory in Rueschlikon (Switzerland) in the Optoelectronics Department. In 1996, he joined the IBM Storage Technology Division in Mainz (Germany) as head of the Laboratory for Magnetic Characterization and Technology Projects. In 2003, he joined Robert Bosch GmbH as project manager for next-generation acceleration sensors. In 2004, he was appointed full professor for the new section—micro- and nanoscale engineering in the Department of Mechanical Engineering of the TU Eindhoven (The Netherlands). In 2012, he was appointed professor at TU Braunschweig (Germany) and became head of the Institute of Microtechnology (IMT). Dietzel's current research interests include sensors and actuators for metrological and aeronautical applications.