Micro Cutting Tool Measurement by Focus-Variation

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Stefan Scherer[1], Reinhard Danzl[2], and Franz Helmli[3]
[1]CEO Alicona*; e-mail: stefan.scherer@alicona.com
[2] Alicona Research*; e-mail: reinhard.danzl@alicona.com
[3]Head of R&D Alicona*; e-mail: franz.helmli@alicona.com
*Teslastraße 8, 8074 Grambach, Austria

ABSTRACT

The ongoing miniaturization of precision engineering parts also requires new micro tools with diameters of a few hundred micrometers and below. So far, the measurement of micro tools has been very difficult. Whereas tactile devices are often not able to efficiently measure micro tools due to their sharp edges and small dimensions, optical systems are usually not able to perform full 3D measurements or are limited with respect to measurable inclination angles. Here we present an optical device based on the Focus-Variation principle that is able to measure micro tools with diameters down to 250 µm and below. The system is not only able to obtain the 3D data but also to determine various important parameters such as diameters, edge radii or surface roughness. After a short description of the measurement technology several measurement results are provided. Among others we demonstrate diameter measurements on a micro drill with a core diameter of ~100 µm and compare edge radius measurements between the presented device and an atomic force microscope. The accuracy is demonstrated by measurements on a calibrated sphere.

INTRODUCTION

As in many industrial sectors, also the tool industry faces an ongoing miniaturization in order to fulfill the requirements for the manufacturing of engineering parts with smallest dimensions. Among others such parts are necessary for medical and dental applications, for the clock industry, for automotive parts and a series of other industrial applications. It is crucial to measure the 3D dimensional shape of the micro tools (drill bits, milling cutters, taps ...), since the form and wear of cutting edges have a strong impact on the manufacturing quality, the manufacturing speed and the lifetime of the tools.

Due to the highly complex geometry, the small dimensions with diameters of a few hundred micrometers and tolerances of a few micrometers, the complete and accurate 3D measurement of such tools is a big challenge. Traditionally, tool measurements are either performed by the analysis of images using back light systems or by using tactile devices that use a contact stylus to obtain the 3D information. However, such tactile systems have several disadvantages when it comes to the measurement of complex tools. First, they have a long measurement time since only a single profile can be captured at once, second the geometry of the stylus tip can falsify the measurement result, and third the wear of the tactile tip and wear of the measured component are undesired side effects. On top of that for very small micro cutting tools, tactile systems are not applicable at all.

The major drawback with the evaluation and analysis of 2D-images is that this method is only possible if no significant areas are hidden in the images. This back-light method is not possible if real 3D-information is required. This applies to tools with concave areas and a variety of parameters of complex tools such as drills or milling cutters.

Apart from this, various optical 3D measurement devices have been developed in the last two decades, which are typically used for surface inspection of parts from one direction. Such devices are typically well suited for the measurement of special aspects of a sample, but not for all. As an example white light interferometric systems are well able to measure smooth samples at high resolution, but face difficulties when it comes to the measurement of samples with steep surface flanks [1] as it is typically the case with tools. Others may be well suited to measure the overall form of a sample (e.g. the diameter) but not the small scale roughness, or vice versa. Finally these devices generally produce so called 21/2D height maps, that are a representation of a surface from one direction, but are not able to perform a complete 360° measurement of tools in order cover the whole geometry and to calculate complex feature parameters.

Here we present a 3D measurement device based on the Focus-Variation principle that is well suited for the measurement of all important aspects of tool 3D measurement. These include measurements of tool parameters that represent the overall form (e.g. diameters, tapering, relief), parameters that represent small scale form features such as the radius of cutting edges that can often be in the range of a few micrometers, as well as parameters that represent the roughness or surface texture of a tool. The device InfiniteFocus (Fig. 1) is equipped with an automated rotation unit that allows to measure a tool not only from one direction but around 360° so that the complete geometry can be obtained. Although we focus here on the measurement of tools the system can also be applied to a wide range of other measurement applications including the measurement of micro components that have been produced by micro tools or other micro-machining applications such as electrical discharge machining (EDM) [7].

In the following we start with a basic description of the measurement principle of the proposed device and then focus on the method for the acquisition of complete 360° measurements. Additionally we give an overview of methods to extract tool parameters from measured 3D datasets. Afterwards we provide several quantitative results showing the ability of the device to accurately measure various tool parameters such as diameters and angles, to measure large and small scale form features as well as the surface roughness.

3D MEASUREMENT OF MICRO TOOLS WITH REAL3D

A. BASIC PRINCIPLE OF FOCUS VARIATION

The optical measurement device which is used for the 3D measurement is the InfiniteFocus device by Alicona which can be additionally equipped with an automated rotation unit (Fig. 1). The technique of Focus-Variation [2][3] combines the small depth of focus of an optical system with vertical scanning to provide topographical and color information from the variation of focus. Its vertical resolution depends on the chosen objective and can be as low as 10 nm. The vertical scan range depends on the working distance of the objective and ranges from 3.2 to 22 mm. The x-y range is determined by the used objective and typically ranges from 0.14 x 0.1 mm to 5 x 4 mm for a single measurement. By using special algorithms and a motorized x-y stage the x-y range can be exceeded up to 100 x 100 mm and more. In contrast to many other optical techniques that are limited to coaxial illumination, the maximum measurable slope angle is not only dependent on the numerical aperture of the objective, however many different illumination sources (such as a ring light) are possible, which allow the measurement of slope angles exceeding 80°. Since the technique is very flexible in terms of using light, most limitations when measuring surfaces with strongly varying reflection properties within the same field of view can be avoided. In addition to the scanned height data, focus variation delivers a color image with full depth of field which is registered to the 3D points. This provides an optical color image which eases measurements as far as the identification and localization of measurement fields or distinctive surface features are concerned.

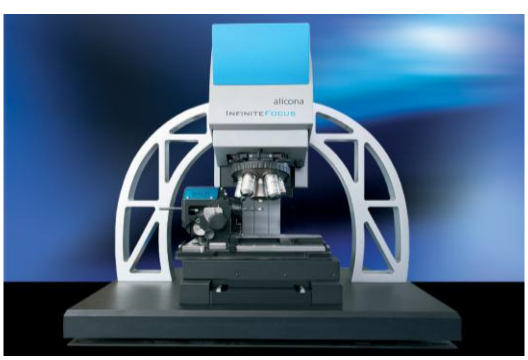


Fig. 1: The InfiniteFocus system with a Real3D unit for the measurement of micro cutting tools and miniature parts around 360°.

Fig. 2: Detailed view of the motorized Real3D rotation unit.

B. MEASUREMENT OF TOOLS AROUND 360°

The crucial component for measurements of tools around 360° is the automated rotation unit (Fig. 2) that can be placed on the top plate of the x-y-stage. For a 360° measurement, the system automatically performs several measurements of the sample from different directions which are then automatically aligned and merged to a full complete 360° dataset. So it is possible to measure even tools with undercuts and complex geometry such as mills or screw taps.

It is important to note that the number of necessary measurements as well as the directions from which the parts are measured are automatically determined by the system and do not have to be set up by the user. Additionally the alignment of the different datasets is also performed fully automatically and does not have to be performed manually as it is the case for many software packages that are available for fusion of 3D datasets obtained from different viewing directions.

C. DETERMINATION OF TOOL PARAMETERS

After the 3D dataset has been acquired a large range of parameters of the tools can be determined such as different diameters, angles, reliefs or the edge radius at different cutting edges. Among others the software includes the following modules for the measurement of certain parameters:

1. A module for the extraction of surface contours for the measurement of parameters such as diameters, the relief and complex tap parameters.
2. A module for the measurement of the geometry of cutting edges including measurements of the edge radius and various angles.
3. A module for the measurement of different form features (sphere radius, cone angle, cylinder radius), e.g. for the determination of the shaft diameter (by using a cylinder fit) or the chamfer angle (by using a cone fit).
4. Two modules for the measurement of surface roughness, one for surface profiles (Ra, Rq, Rz ...) and one for whole areas (Sa, Sq, Sz ...) as specified in recent ISO standards for area based surface texture measurement [6].

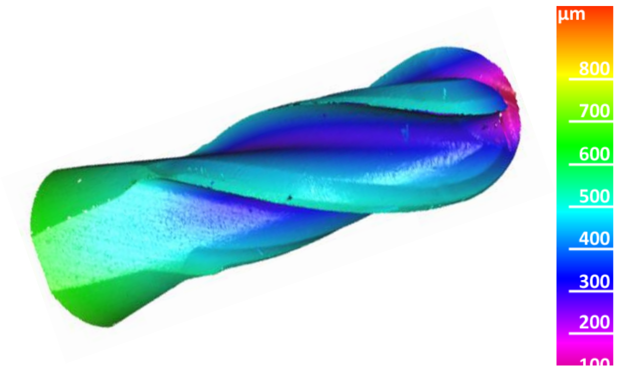


Fig. 3: 3D dataset of a measured micro milling cutter. The colors represent the distance to the tool axis.

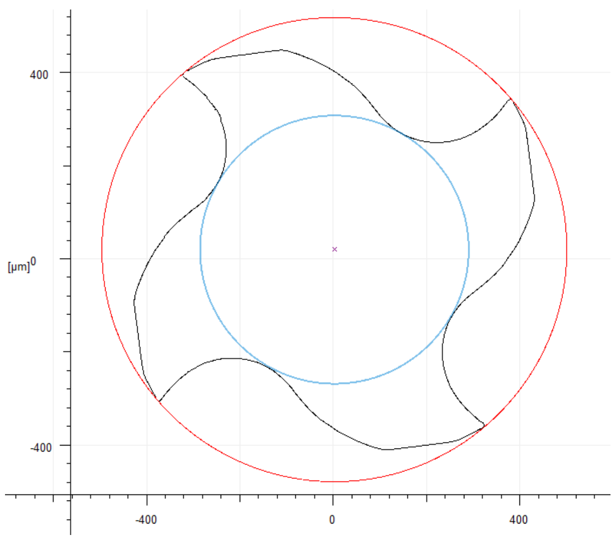


Fig. 4: Extracted profile contour of the measured micro milling cutter. Red circle: Outer diameter. Blue circle: Core diameter.

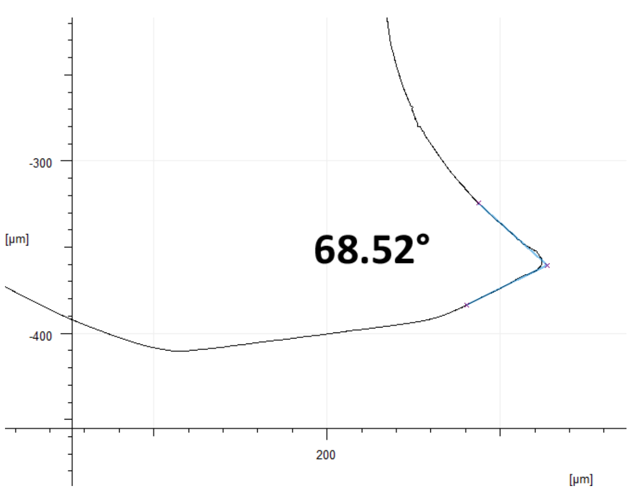


Fig. 5–Detailled view of rake angle measurement from the extracted contour. The two lines that have been fitted for angle measurement are shown in blue color.

As an example for a typical measurement application we show in the following the measurement of the major and core diameter as well as the rake angle of a micro milling cutter with an approximate diameter of about 1mm. In Fig. 3 the 3D dataset that has been measured with the proposed Infinite-Focus device is shown. The different colors represent the distance to the tool axis. From this dataset a surface contour has been extracted (Fig. 4) that has been generated by intersecting the dataset with a plane that is perpendicular to the tool axis. From the surface contour profile the core diameter has been extracted as 288.28 µm (blue circle in Fig. 4), those of the outer diameter as 498.87 µm (red circle in Fig. 4). Additionally the measurement of the rake angle at one cutting edge is visualized as provided in Fig. 6, which has been made by fitting two lines (blue) into the surface contour (black).

RESULTS

In order to evaluate the performance of the proposed system various quantitative experiments have been performed. For each of the most important measurement aspects in the previous section (tool parameters, edge radius, large scale form, surface roughness) a quantitative evaluation is provided.

Measurements on a micro drill are shown in section A where the minor and major radius have been measured at different axial positions using extracted surface contours. Section B contains an evaluation of the measured edge radius of an edge calibration tool that has once been measured with the proposed system and once with an atomic force microscope. The accuracy of form measurements of the system has been evaluated by measuring calibration spheres with a diameter of 10 mm (Section C). Finally an evaluation of surface roughness is provided in Section D where measurements of the proposed system are compared to a tactile instrument.

A. MEASUREMENT OF TOOL PARAMETERS OF A MICRO DRILL

In order to evaluation the performance of the system for micro tool measurement a micro drill bit with a major diameter of ~250 µm has been measured by the device (Fig 6). In order to evaluate the quality of the measurement the core and major diameter of the drill bit have been determined by cross sections and consecutive fits of circles into the 2D contour as shown in Fig 7. The diameters have been estimated at different axial positions as provided in Table 1 showing that the major radius stays almost constant over the evaluated range of 300µm whereas the core radius linearly decreases towards the tip. The standard deviations of the major radius as well as the standard deviation of the differences between the core radius and a regression line, which have been fitted into the core radius values, have been both in the range of about 0.19µm showing the good quality of the measurement. The change of the two parameters with respect to the axial position is also visualized in two diagrams, in Fig. 8 showing the linear decrease for the core radius (upper diagram) and the constant progression of the major radius for different axial positions (lower diagram). The upper diagram shows the measured core radius (blue) and the regression line (orange).

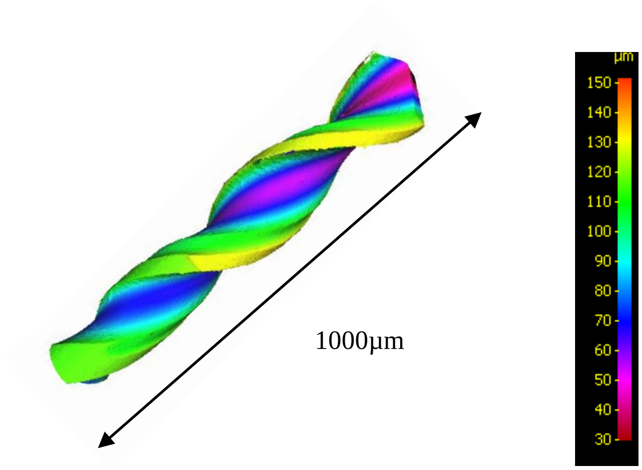


Fig. 6: Measurement of a micro drill bit with Focus-Variation. The colors represent the distances to the axis of the tool.

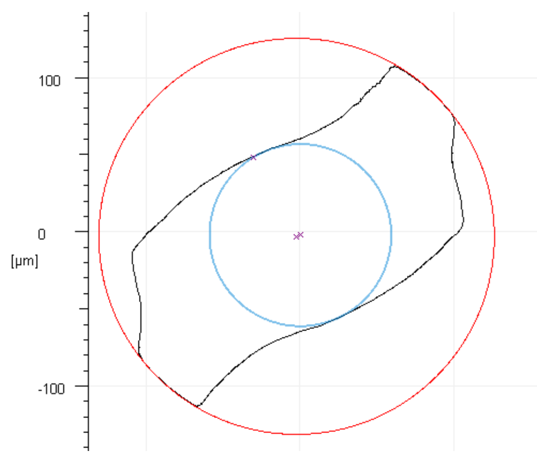


Fig. 7: Measurement of a micro drill bit with major diameter of~250µm. Extracted contour profile (black) with fitted circles for major (red) and core diameter measurements (blue).

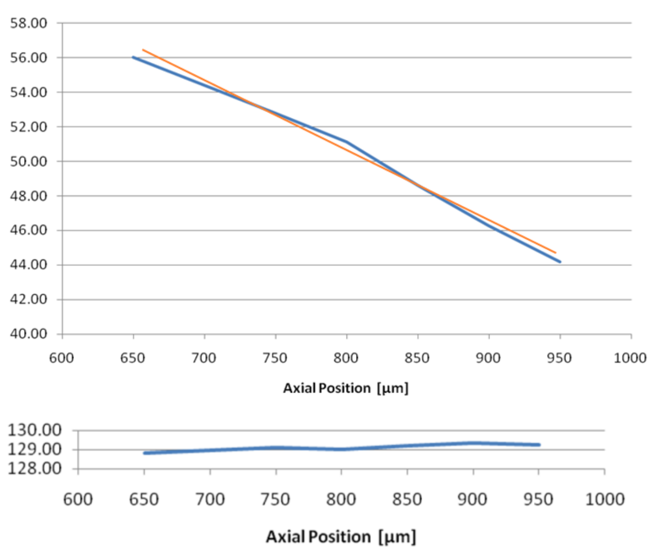


Fig. 8– Upper diagram: Core radius at different axial positions (blue) and fitted regression line (orange). Lower diagram: Major radius at different axial positions.

Table 1 - Measurement of the core and major radius of a drill bit at different axial positions. The standard deviation of the major radius is only 0.192µm. The values in the table are in [µm].

#	Axiale Position	Major radius	Core radius	Regression line for core radius	Deviation to regression line
1	650	128.80	56.03	56.48	+0.45
2	700	128.95	54.40	54.48	+0.08
3	750	129.10	52.78	52.48	-0.29
4	800	129.01	51.12	50.48	-0.63
5	850	129.20	48.61	48.49	-0.12
6	900	129.36	46.26	46.49	+0.23
7	950	129.25	44.20	44.49	+0.29
Std. dev.		0.192µm			0.190µm

B. EDGE RADIUS MEASUREMENT OF AN EDGE MEASURMENT STANDARD

In addition to tool parameters that describe the overall geometry of the tool such as the major diameter, the tapering, or the chamfer, it is often important to measure small scale form features such as the cutting edge radius [5]. In order to show that the presented device can also measure very small radii down to a few micrometers a comparison of edge radius measurements between the proposed device and an atomic force microscope (AFM) has been performed.

An important aspect is the way how the edge radius is determined from the extracted surface profile. Instead of manually fitting a circle into the top region of the profile, which would be not very repeatable due to the user influence an edge model is fitted into the data consisting of a circle with two adjacent tangent lines. This allows the measurement of the radius without ambiguity.

In Fig. 9 the 3D datasets of the measured edge calibration standard are presented that have been measured by the Focus-Variation system and by an atomic force microscope from NanoSurf. In Fig. 10 two extracted surface profiles are shown together with the measured edge radii (red circle). The measured 3D datasets and the extracted surface profiles have a very similar shape and the measured edge radii of 2.51µm (InfiniteFocus) and 2.41µm (AFM) as provided in Table 2 have only a difference of 0.1µm, showing the ability of the optical device to measure even very small lateral and vertical structures.

In addition to the measurement of the surface radius additional other parameters of the edge can be automatically determined including chipping, clearance and rake angle, the bevel geometry. Moreover it is also possible to measure cutting edges that do not have circular shape but are elliptical.

Table 2 – Comparison of edge radius measurement between Focus-Variation and an atomic force microscope (AFM).

	AFM	Focus-Variation
Measured edge radius	2.41µm	2.51µm

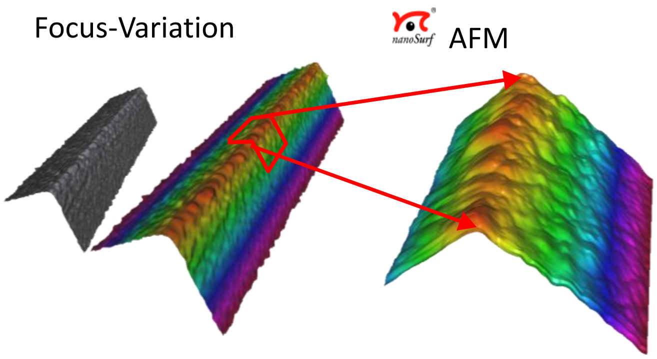
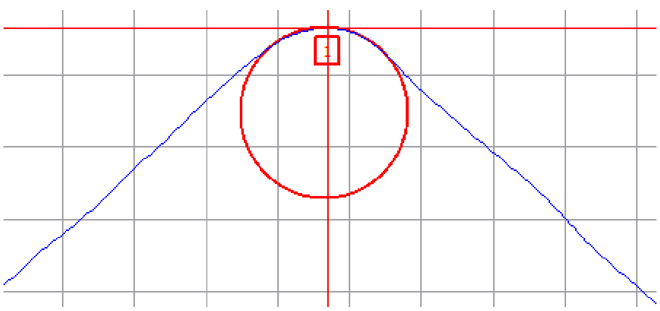
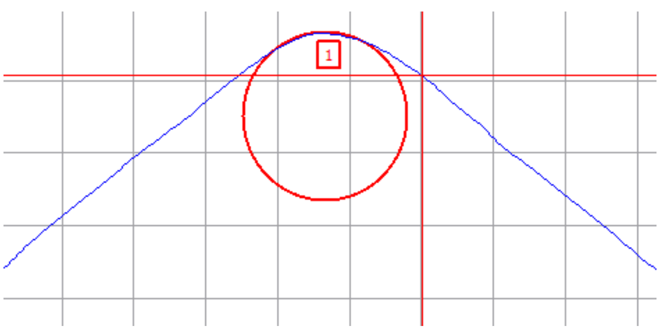


Fig.9: Comparison of cutting edge radius measurement between Focus-Variation and an atomic force microscope.



Focus-Variation: 2.51µm



AFM: 2.41µm

Fig. 10: Comparison of cutting edge radius measurements between Focus-Variation and an atomic force microscope. Each grid cell in the edge contour graphs represents 2µm. Blue: measured surface profile. Red: Fitted circle for radius measurement.

C. FORM MEASUREMENTS OF A CALIBRATION SPHERE

In order to evaluate the accuracy of Real3D measurements a calibration sphere with a nominal radius of 5mm has been measured around 360°. The dataset in Fig. 11 shows the measured sphere with its original color that is provided by the measurement device whereas the dataset in Fig. 12 shows the deviations between the measured data and a fitted sphere.

The radius calibrated as difference measurement to a reference sphere with an Abbe comparator was 5.0006mm. That measured by InfiniteFocus was 5.0009mm thus having a difference of 0.3µm. The form deviations are in a range of +/-0.6µm. As shown in Fig. 12 the deviations are very evenly distributed over the whole sphere.

Additionally a cross-section of the calibration sphere has been performed and a roundness profile has been generated as provided in Fig. 13. The red circle represents the circle fitted in a least squares sense whereas the deviations to this fitted circle are exaggerated for better visualization. The deviations are between -0.4µm and +0.25µm for the visualized surface profile.

Table 3: Comparison of sphere radius measurement between Focus-Variation and an Abbe comparator

	Abbe Comparator	Focus-Variation
Sphere radius	5.0006mm	5.0009mm

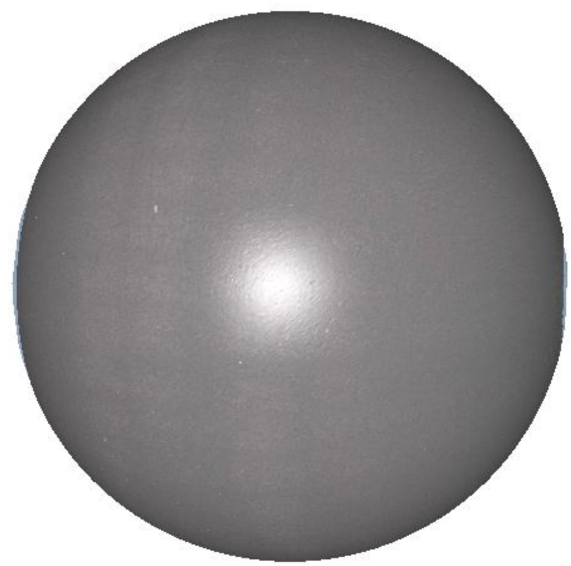


Fig. 11: Measurement of a calibrated sphere with true colors.

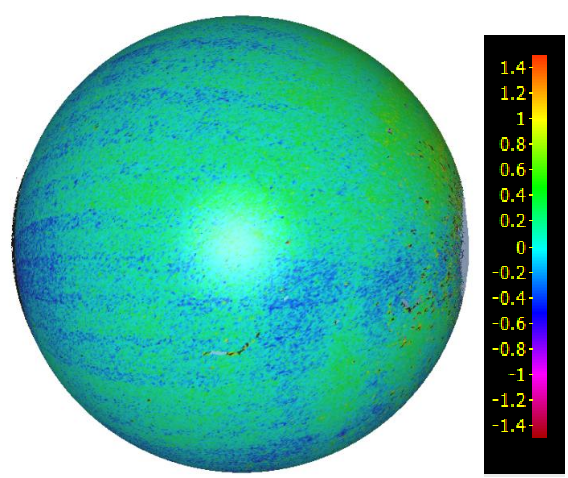


Fig. 12: Measurement of a calibrated sphere with pseudo colors where the different colors represent the difference of the measurement points to the fitted sphere. The scale is in [µm].

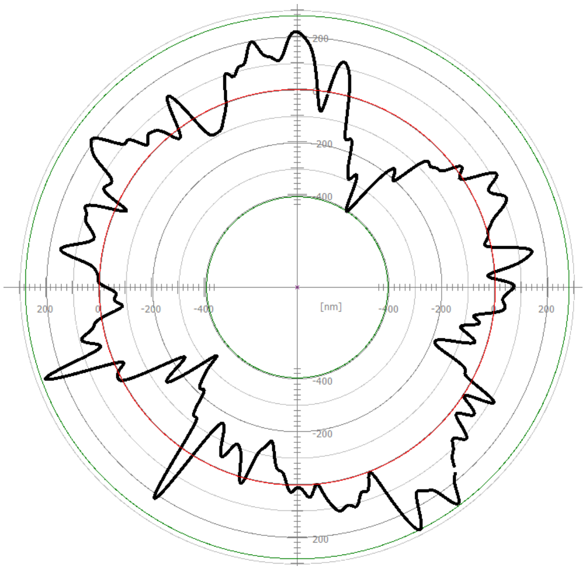


Fig. 1: Roundness profile generated by a planar cross section through the measured calibration sphere. The deviations to the fitte circle (red) are scaled and lie between -400nm and +250nm

D. SURFACE ROUGHNESS MEASUREMENT

For many applications it is not only necessary to measure different form parameters of a tool but also the surface roughness, since e.g. the surface roughness in the flute determines how well chipped material can flow off.

In order to evaluate whether the system is able to measure small-scale roughness a roughness standard with a nominal Ra value of 120nm has been measured with a tactile system and with the proposed device. The 3D dataset of the standard is provided in Fig. 14 showing the random structure along the x-direction and the regular structure along the y-direction as it typical for many random roughness standards that are typically developed for tactile devices that only measure surface profiles.

The measurements of the tactile device been performed at 9 different positions, those of the Focus-Variation instrument at 10 positions. The measurement length was 1.25 mm and the Lc cutoff value for waviness filtering was 0.25 mm. The measurements by InfiniteFocus have been performed with a 100x objective and a vertical resolution of 10 nm.

The results for the mean Ra value and the standard deviation at the different positions are presented in Table 4. Both, the mean Ra value as well as the standard deviation are in a similar range. In Fig. 15 a surface detail of the measured profile is shown where the random structure of the standard is visible. The profile shows that also very small lateral surface structures can be measured, e.g. is the lateral distance between the two valleys is only 5.5µm which means that the optical device can measure very small lateral structures.

Table 4 – Comparison of surface roughness measurement between a tactile device and the proposed system.

#	Tactile device	Focus-Variation
Mean Ra	120 nm	121nm
Standard deviation	3nm	3nm

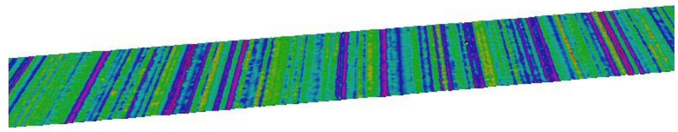


Fig. 14: 3D dataset of the measured random roughness standard. The range of the pseudo colors that represent the depth lies in the range of +- 400nm.

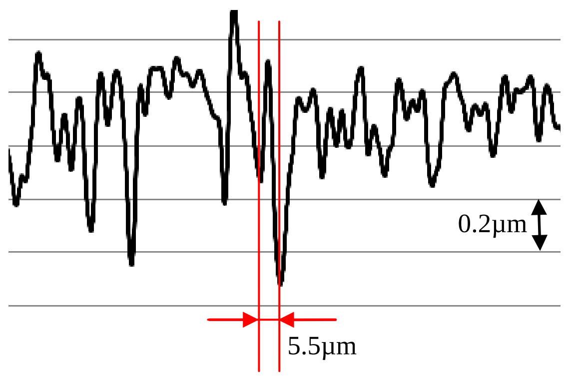


Fig. 15: Surface detail of the measured roughness profile. The diagram shows that also lateral structures with small wavelengths (<6µm between two valleys in this case) can be measured.

CONCLUSIONS

We have presented an optical metrology device that can be used for the measurement of micro tools and machined parts. In contrast to many other devices the system is able to perform full 360° measurements of samples and allows the measurement of a wide range of different parameters that characterize micro tools such as diameters, edge radius and surface roughness.

An evaluation of the major radius of a drill bit has shown the ability of the system to measure small parts with a core diameter of ~100µm with standard deviations in the nanometer range. Comparisons of edge measurements to an atomic force microscope demonstrate the ability to measure small scale features such as edge radii of 2.5µm with very similar results (deviation 0.1µm). Measurements on a calibrated sphere show the accuracy of the system with deviations in the sub-micrometer range that are evenly distributed over the whole sample. Evaluations on random roughness standards with a nominal Ra of ~120 nm demonstrate the ability to accurately measure small scale surface roughness as it is necessary e.g. when the roughness in the flute of a tool shall be analyzed.

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