Optical Measurement of Micro Cutting Tools

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Abstract. We present an optical measurement device for the complete 3D measurement of very small micro cutting tools with diameters down to 100µm and below. Such micro tools can be hardly measured by conventional devices such as tactile systems due to their complex geometry and small dimensions. The used optical device is based on the Focus-Variation principle which combines the small depth of focus of an optical system with vertical scanning to provide topographical and color information from the variation of focus. Full 360° measurements of the tools are automatically measured in a two step procedure. First, single measurements are performed from different directions all around the specimen with the aid of a motorized rotation unit. Then all single datasets are automatically aligned and merged to a full 360° dataset. Various measurement results are presented for milling cutters and drills including tools with diameters in the range of about 50µm. From the measured tools various parameters can be obtained including the major diameter, the core diameter or various angles. Additionally roughness measurements are provided on small cutting tools showing the versatility of the system for both form and roughness measurements.

1. Introduction
The 3-dimensional measurement of cutting tools, drills and milling cutters with diameters in the micro range (e.g. smaller than a few hundred microns) has become an essential aspect in quality assurance. Form and wear of a cutting edge have a strong impact on the manufacturing quality. The dimensional accuracy significantly influences the manufacturing speed as well as the lifetime of a tool. Due to the highly complex geometries (e.g. steep flanks, relief...) the 3D-measurement has become a big challenge for optical measurement devices.

Traditionally, tool measurements are merely performed by tactile measurement devices or with the analysis of images using back light processes. One disadvantage of tactile systems is the long measurement time. Another one is the fact that the geometry of the stylus tip falsifies the measurement result. On top of that, wear of the tactile tip and wear of the measured component are undesired side effects. Moreover, for very small micro cutting tools, tactile systems are not applicable at all. The evaluation and analysis of 2D-images 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.

A typical example for a measurement device especially designed for the measurement of tools is the Helicheck device [1]. This is equipped with a tactile probe and up to four cameras for optical 2D measurements from different directions. Additionally it can be extended by a module for the

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measurement of the cutting edge roundness. However, this device does not deliver dense 3D measurements of the whole tool and has limitations when it comes to the measurement of very complex tool parameters. In contrast to such devices that are optimized for tool measurements and also deliver tool parameters in addition to 3D data, miniature coordinate measurement machines (CMM) are available, that are able to measure arbitrary samples (not only tools) from different directions. An example for such CMMs is the F25 device [2] from Carl Zeiss, which consists of a tactile probe and additional cameras for optical 2D measurements. Although this device has a very high accuracy the tactile measurement of very small tools can be problematic due to the above mentioned limitations of tactile probes.

Within this paper a new system for 360° measurement of complex tools is introduced. The InfiniteFocus system (Figure 1) is based on the technology of Focus-Variation [3] [4] and is equipped with a motorized rotation unit. In the first step various measurements are performed at several angles. In step two the single measurements are automatically aligned to each other. As a result a full 360° dataset is available for all further measurements. Geometric primitives can as well be measured as it is possible to analyze contours. Most measurement systems that were available up to now have the decisive disadvantage that they can only measure rather simple parameters as for example the major diameter. For complex parameters a highly complex and time consuming measurement process must be performed. The presented system in contrast does not only measure the full 3D-dataset in high resolution but also delivers complex tool parameters [5]. Parameters such as flank diameter, chipping angle or thread diameter are easily measured. Additionally a variety of roughness parameters can be measured.

Figure 1. (a) InfiniteFocus – optical 3D micro coordinate measurement system (b) Rotation and tilting unit for rotating the specimen and performing measurements of 360°.

2. 360° Measurement of Complex Components

The optical 3D-measurements, shown in this paper, were measured with the measurement device InfiniteFocus from Alicona This system is based on the technology of Focus-Variation. This technology especially well handles steep flank measurements. Exactly this ability is necessary for measuring micro drills, micro components or tap tools. The technique of Focus-Variation [3] [4] combines the small depth of focus of an optical system with vertical scanning to provide topographical and color information from the variation of focus. In order to perform 3D measurements the device vertically scans the specimen by the sensor while continuously acquiring data. Since the system has a limited depth of field only small parts of the object are imaged sharply at the same time. By analyzing the variation of focus during the scanning process a 3D-dataset is obtained. The standard system is able to measure surfaces from one direction and to deliver a height value for each x/y position in the field of view. For measuring a tool around 360° a special rotation and tilting unit (Figure 1b) has been developed. This unit allows tilting the tool between 0° and 90° and an endless rotation around 360°. The rotation unit includes a special clamping fixture which allows highly accurate positioning of the tool. The number of required measurements is calculated automatically and is dependent on several
parameters. Important factors are the size of the used field of view, the diameter of the tool, the tilting and the scan height. In a second step the alignment is performed in order to receive a highly accurate 360° dataset and to reduce the small but existent error of the rotation axis calibration. In step three all single measurements are combined with a special algorithm resulting in a 360° dataset.

3. Results
In the following examples of drills and milling tools show the scope of the measurement device. In Section 3.1 a drill bit with a major diameter of 260µm is presented, whereas Section 3.2 contains measurements of a micro milling cutter with a diameter of around 70µm.

3.1. Complex Geometry Measurement of a Drill
In Figure 2 the measured micro drill is displayed in pseudo color. The colors represent the distance of every measurement point to the tools’ axis. This drill has been measured with the previously presented measurement device InfiniteFocus and its rotation unit. A cutting layer is displayed in Figure 3. The cross section of this dataset is given in Figure 4. By using the contour measurement the major radius of 128.8µm (circle 1) and the core radius of 59.2µm (circle 2) were measured. Since the dimensional accuracy of a drill has a big influence on manufacturing quality it is important that the drill is produced exactly the way it is thought to be. The measured radius of circle 3 is 97.1µm and those of circle 4 97.4µm. There is only a difference of 0.3µm.

In order to evaluate the accuracy of the measurements the core and major radius has been measured at seven different axial positions in a range of 300µm as shown in Table 2. An axial position of 500µm corresponds to the cross section shown in Figure 3. The tip position corresponds to an axial position of 1050µm. The major radius stays merely constant over the whole range whereas the core radius linearly decreases towards the tip position.

For the major radius a standard deviation of 0.192µm has been measured which is very small for a micro drill measurement. In order to evaluate a useful standard deviation for the core radius a regression line has been fitted into the measured core radius values and the deviation to this regression line has been calculated. The standard deviation of these deviations is 0.19µm and thus very similar to those of the major radius. The trend of the major and the core radius is visualized in Figure 5.

![Figure 2. 360° Measurement of a micro drill with major radius of about 130µm. The bounding box is 0.26 x 0.26 x 1.08mm.](image1.png)

![Figure 3. Measured micro drill with extracted cutting layer for contour measurement. The bounding box is 0.26 x 0.26 x 1.08mm.](image2.png)
Figure 4. Contour measurement including several circle measurements and showing the areas for the cutting edge detail A and B. The coordinate center (0/0) is the center of circle 2. The y-scale ranges from -200 to +150µm the x-scale from -350 to +350µm.

Figure 5. Upper diagram: Core radius at different axial positions; Lower diagram: Major radius at different axial positions.

Table 1. Measurement of the major and core radius at different axial positions (all values are in µm).

| Number | Axial Position | Major Radius | Core Radius | Regression Line | 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                       |
| Standard Deviation | 0.192          |              | 0.190        |                 |                            |

Figure 7. (a) Section of Detail A. (b) Detail A (showing a y-scale ranging from -610 to -550µm and an x-scale ranging from +140 to +230µm). (c) Detail B (showing a y-scale ranging from +340 to +380µm and an x-scale ranging from -150 to -100µm).
Figure 8. (a) 2D-view of the drill tip with the marked area used for the roughness measurement (Dimension of the marked area: 40 x 75µm). (b) Filtered surface used for calculation of roughness parameters. The height values range from -0.5 (dark) to 0.5µm (bright). (c) Roughness Measurement results of (b).

The standard deviations calculated above only provide parts of the measurement uncertainty including the repeatability of the measurement and the uncertainty of the sample. In order to get additional information on the measurement uncertainty for typical tool parameter measurements, the pitch diameter of a calibrated thread plugs has been measured. Our measurement result for a thread plug with the calibrated value of 1.7347mm was 1.7353mm leading to a difference of 600nm. Our measurement result for a thread plug with a diameter of 7.4054mm was 7.4071mm leading to a difference of 1.7µm. The measurement uncertainty of the device used for calibration was ±2.5µm, thus both of our measured values were in the uncertainty range of the calibrated device.

One big advantage of the technology Focus-Variation is the ability of measuring steep flanks. This enables cutting edge measurements with angles up to 20°. For cutting edge measurements it is especially important to measure with a cross section normal to the cutting edge. The cross section of Detail A is shown in Figure 7a. Detail A and B are shown in Figure 7b and 7c. The cutting edge angles are 56.22° for Detail A and 55.83° for Detail B.

In addition to form measurements also roughness measurements can be performed due to the high measurement point density. The measurement shown in Figure 8 is a roughness measurement on the tip of the drill from section 3.1. Figure 8b shows the roughness filtered dataset of the area marked in Figure 8a. Different area based roughness parameters [6] are shown in Figure 8c.

3.2. Measurement of a Micro Milling Cutter

Up to now a big challenge for 360° measurements were components smaller than 100µm. But especially in this range dimensional accuracy is more important than ever. Only a small deviation may result in a short tool life time or in inaccurate manufacturing results. The presented measurement device in combination with the rotation unit enables measurements of components with a diameter as small as 70µm. Shown are two example measurements. Figure 9 and 10 depicts the 360° measurement of the micro milling cutter and shows the result of the cutting tip measurement. The longitudinal cross section is aligned along the rotation axis of the milling cutter.
4. Conclusions
We have demonstrated the measurement of small tools using an optical measurement device based on Focus-Variation. Measurements of the major radius on various positions of a drill with a standard deviation as small as 190 nm show the accuracy of the proposed method. Comparisons of pitch diameter measurements of a thread plug to calibrated reference values showed differences that were within the calibration measurement uncertainty of 2.5 µm. Measurements on a micro milling cutter demonstrate the ability to measure even tools with diameters below 100 µm. In addition to form measurements also roughness measurements (e.g. at the tip of a drill) are applicable due to the high measurement point density of Focus-Variation.

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