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3D optical inspection of cutting tool geometry

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Abstract

The quality control of high precision cutting tools is essential for increasing tool life and efficiency in research as well as directly in the production. In addition to surface roughness measurement and the wear behaviour, the measurement of the microgeometry of cutting tools is challenging in 3D metrology due to the high variety of complex geometries with very small dimensions. The proposed measurement instrument offers advantages in terms of accuracy, non-contact measurement as well as the ability to measure steep flanks and the full 3D form of cutting tools. Here, a 5-axis optical measurement device based on focus variation is presented which can be used for highly accurate cutting tool inspection. The performance of the measurement instrument is shown by repeated measurements on several micro geometries on a calibrated edge tool. Moreover, 3D measurements of round tools with several dimensions show the capability of the measurement instrument for full micro form measurements and their optical geometry and roughness inspection.

Keywords: Focus variation, cutting edge microgeometry measurement, round tool inspection

1. Introduction

Optical 3D metrology became more and more important in tooling industry where the requirements regarding dimensions, manufacturing tolerances and machining results increase continuously. Therefore, the use of measurement technology for quality assurance is indispensable, both in research and in production. In order to assess the quality of high precision cutting tools such as drills or indexable inserts it is necessary to measure their exact micro-geometry. The challenges here are the complex, ever smaller geometries, as well as the wide variety of different material from which the tools e.g., drills, milling cutters, inserts are made. In addition, the measurement instrument must be able to capture steep flanks as well as the complete 360° geometry of the entire tool.

The cutting edge preparation has a decisive influence in the tool life and hence on the economic efficiency of cutting tools. Therefore, the edge geometry, the surface roughness as well as the wear behaviour are important criteria for the metrological quantification. Wear and cutting edge breaks are one of the most common problems with regards to tool life behaviour. Cutting edge microgeometry influences, among other things, the cutting edge retention, the stability, the cutting force as well as the susceptibility to cutting edge breaks. The cutting edge microgeometry can be described by a wide variety of different parameters. When measuring them, it is crucial to describe the cutting edge profile optimally. There is a wide variety of different characterization methods [1,2,3,4] describing the geometry by e.g., the edge radius, the rake and clearance angle, the projected rounding on flank face and rake face or different symmetry factors. The importance of the cutting edge characterization has also been taken up from the Association of German Engineers (VDI) as the development of a series of standards is currently being developed. Many cutting edge parameters, which serve to characterize the rounding of the cutting edge were standardized in VDI 2654 [3] for the first time.

Optical measurement instruments like white light interferometry, structured light, confocal or focus variation [4,5,6,7] have become very popular for measurement applications in tooling industry. In contrast to profile-based stylus methods, they enable fast, contact-less, and therefore damage-free, area-based measurements. However, many optical measurement instruments are limited in their application range because they are either designed for high-resolution roughness measurements or for form measurements. Moreover, these optical measurement instruments are limited with respect to the measurable slope angle. Unlike other optical measurement principles such as confocal or white light interferometry, focus variation is not limited to coaxial illumination. Using many different light sources such as coaxial, ring light, polarization or transmitted light focus variation measurement instruments enable the measurement of slope angles up to 87° degrees and more [6,8].

In this paper, the optical inspection of cutting tools by focus variation is presented. First, the measurement technology and the used measurement device are described. Afterwards the performance of the system is demonstrated by several measurements of a calibrated edge tool. Finally, the optical inspection of round tools is shown.

2. 3D measurement of cutting tools

2.1. Focus variation measurement instrument

In this paper, an optical measurement instrument based on focus variation is used for the measurement of cutting edge micro geometries and 3D round tools (see Figure 1). It can be equipped with several objective lenses (5x, 10x, 20x, 50x, 100x) and optionally by a ringlight. Moreover, a polarizer can be activated dependent on the tool geometry and surface characteristic to be measured. For a complete 3D measurement of a round tool, the measurement instrument can be extended to a 5-axis device by mounting an automatic rotation- and tilt unit on the

Figure 1: The InfiniteFocus G5+ measurement instrument with a focus variation sensor and equipped with a motorized rotation- and tilt unit for a complete 3D measurement of micro tools.

Figure 2: Edge calibration tool calibrated by METAS for the verification of optical cutting edge measurements.

x-y-stage to rotate the tool during the measurement.

Focus variation (see [6,7,8,9]) is an optical measurement principle which uses the small depth of focus of an optical system in combination with a vertical scanning method. Typically, the optical sensor is moved vertically along the optical axis and images are captured continuously. Due to the small depth of focus and the vertical movement of the sensor, the focus for each point varies over the scanning process and for each point a focus information curve along the vertical axis can be generated. Different algorithms can be used to compute the topographical information and the true colour information.

The instruments software allows an automatic measurement of user-defined geometry and roughness parameters of inserts and round tools. In addition to many cutting edge parameters describing the microgeometry, the software has additional modules for evaluating the round tool geometry as well as the surface roughness, the edge quality of cutting edges and wear parameters on the basis of a dataset series.

3. Results

2.3. Cutting edge preparation

In order to verify the performance of the measurement instrument for cutting edge microgeometry measurements, several measurements on an edge calibration tool (see Figure 2) calibrated by METAS (Federal Institute of Metrology, Berne/Switzerland) have been performed. The tool consists of 10 edges with radii between ~3 µm and 75µm and wedge angles between 70° and 110°. The edge shape is either symmetrical which can be described by the radius of a circle or asymmetric (with a K-factor of around 1.5.) which can be described by an ellipse.

The measurement was performed using the InfiniteFocus G5+ without rotation- and tilt unit. For the experiment four edges have been selected: two symmetric edges with a wedge angle of 90° and a radius of 2.6 µm and 8.9 µm, one edge with a wedge angle of 70° and a radius of around 24 µm, and one asymmetric edge described by an ellipse and a wedge angle of 90°. Edge 1 and Edge 2 were measured using a 50x magnification objective lens, Edge 4 and Edge 9 were measured using a 20x magnification objective lens.

On each 3D dataset 50 single profiles have been extracted by an orthogonal cutting plane. Each edge parameter has then been computed on the mean profile.

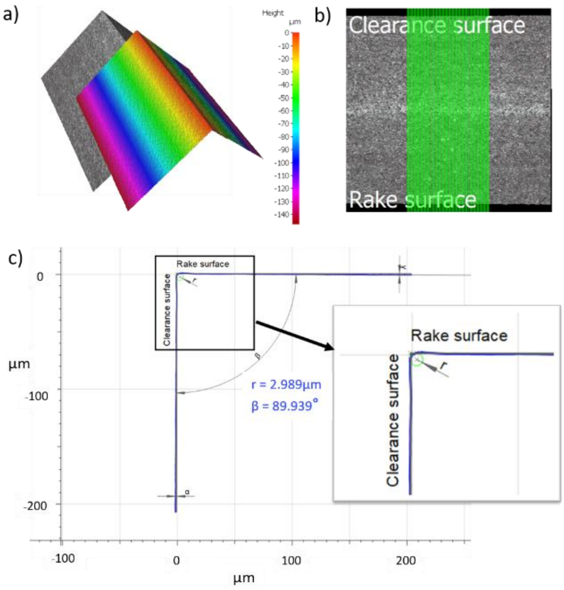
Figure 3 exemplarily shows the measurement results for Edge 1. The top of Figure 3 shows the measured 3D dataset as well as the area where the 50 profiles were extracted. In the middle of the Figure (Figure 3 c &d) the mean profile, which was calculated from the single profiles, and the edge parameters computed on this mean profile were presented with r = 2.989 µm and a wedge angle β = 89,939 °. Finally, Figure 3 shows the radius calculated for each of the single profiles. The deviations in the radii can have different reasons but are mostly caused by e.g., micro surface defects or noise. For this reason, these radii are not as meaningful as those parameters calculated on the mean profile, which are more robust.

The quantitative values compared to the calibrated values are summarized in Table 1 for one measurement per edge. All measured values are very closely to the calibrates results and definitely below the allowed tolerances. For Edge 9, the asymmetric edge, an ellipse (Eα and Eγ for the ellipse half axis lengths) has been used to describe the edge rounding.

Table 1
Results for one measurement on the edge calibration tool for four different edges. The uncertainty of measurement is stated as the combined standard uncertainty multiplied by a coverage factor k = 2.

Name	calibrated	measured	dev.	unit
Edge 1-radius	2.6 ± 0.7	2.99	-0.39	µm
Edge 2-radius	8.9 ± 1.1	8.31	0.59	µm
Edge 4-radius	24.21 ± 0.49	24.10	0.11	µm
Edge 9-Eγ	14.6 ± 0.8	14.7	-0.1	µm
Edge 9-Eα	20.8 ± 1.4	19.63	1.17	µm

To show the accuracy and repeatability, the measurement was repeated 5 times for each edge and the mean as well as the standard uncertainty was calculated. Edge 1 has a mean of 2.99 µm with an associated type-A standard uncertainty of 0.24 µm. Edge 2 has a mean of 8.12 µm with an associated type-A standard uncertainty of 0.16 µm. Edge 4 has a mean of 24.12 µm with an associated type-A standard uncertainty of 0.04 µm. Edge 9 has a mean of 14.66 µm for $E\gamma$ (19.51 µm for $E\alpha$) with an associated type-A standard uncertainty of 0.07 µm (0.18 µm).



d)

Name	Value	Unit	Description
r	2.989	µm	Mean radius of mean edge
α	-0.283	°	Clearance angle
β	89.939	°	Wedge angle
γ	0.344	°	Rake angle
φ	0.000	°	Symmetry angle
Sα	2.468	µm	Dist. apex to end of clearance roundness
Sγ	3.103	µm	Dist. apex to end of rake roundness
K	1.257		Symmetry of cutting edge
Ka	1.410		Symmetry of cutting edge (area)
Δr	1.261	µm	Min. dist. of edge to apex

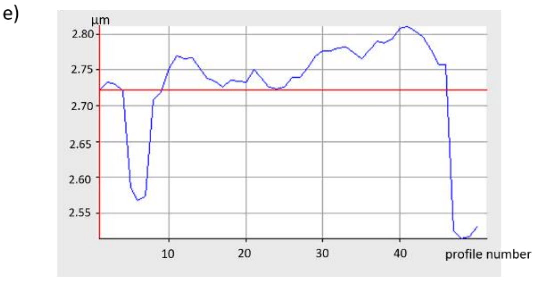


Figure 3: Cutting edge measurement of Edge 1 of the edge calibration tool a) 3D dataset of the edge in true colour and pseudo colour. b) 50 profiles extracted on the 3D dataset. c) Measurement result on the mean profile with r = 2.989 µm and a wedge angle β = 89,939 °. d) Selected cutting edge parameters computed on the mean profile computed on the single profiles. e) Radius computed on each of the 50 single profiles.

2.3. 3D Tool geometry

In order to evaluate the measurement instrument for the optical inspection of round tools with different dimensions, a complete 3D measurement of a micro drill with a nominal diameter of around 60 µm and a screw tap with a nominal diameter of around 1.1 mm were performed. Moreover, several round tool parameters of the screw tap were computed.

For the measurements, the measurement instrument was equipped with an automatic rotation- and tilt unit for a complete 360° measurement of the tool. Using the instruments software, the round tools are measured at various rotation and tilt angles. These single measurements were automatically aligned and then precisely merged into a complete 3D dataset (see Figure 4 and Figure 5 for the measured 3D datasets in true colour and pseudo colour). Figure 6 shows the results of some typical round tool parameters calculated on the screw tap by the instruments software by the use of cross sections. The instruments software provides several modules for surface texture and form measurements on the measured 3D dataset. In Figure 6 top the parameters have been calculated based on a cross

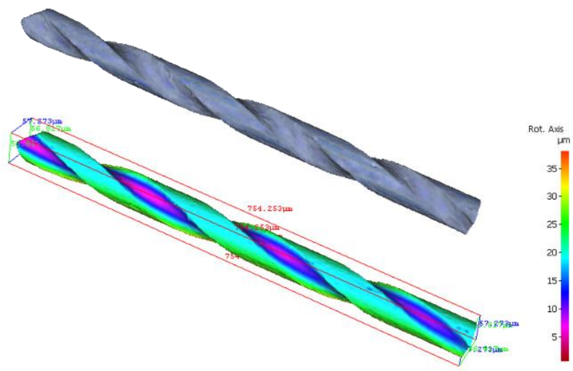


Figure 4: 3D dataset of a micro drill in true colour and in pseudo colour. The diameter of the drill is around 60µm, the length around 750 µm. The micro drill was measured using a 50x magnification lens.

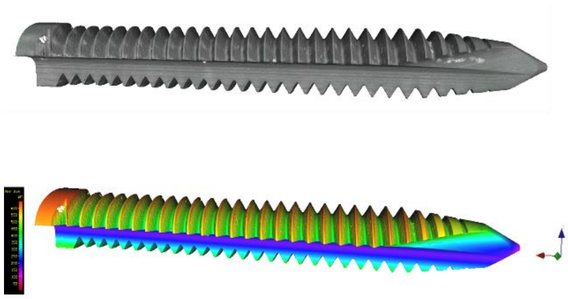


Figure 5: 3D dataset of a screw tab in true colour and in pseudo colour. The tab was measured using a 10x magnification lens and the polarizer was activated.

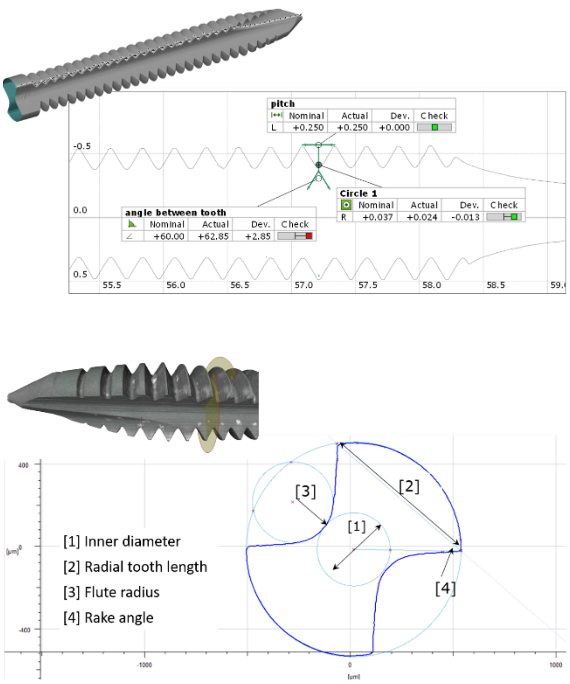


Figure 6: Tool geometry inspection. Top: Evaluation of pitch, thread angle and ground radius by a cutting plane along the tool axis. Bottom: Evaluation of several parameters (inner diameter, radial tooth length, flute radius and rake angle) on the cross section of a helical cutting plane.

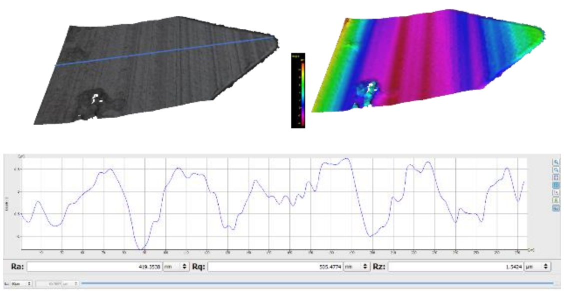


Figure 7: Profile roughness on the chipping surface of the screw tap. The surface was measured using a 100x magnification lens. The calculated values are Ra = 419.35 nm, Rq = 505.48 nm and Rz = 1.54 µm.

section generated by a cutting plane along the tool axis. As it can be seen in Figure 6 top, values are highlighted to show if they are within the allowed tolerances. In Figure 6 bottom, first a cross section was generated by the use of a helical cutting plane that can be placed manually by the user. The tool parameters were calculated by the geometric inspection of the extracted contour e.g., the radius and the diameter were automatically calculated by inner and outer circle fits on measured points. The screw tap has a measured inner diameter of 0.356 mm, a radial tooth length of 0.797 mm, a flute radius of 0.196 mm and a rake angle of 4.76°.

In addition to geometrical parameters, also the surface roughness of a cutting tool may be of interest. Finally, to demonstrate that the presented measurement instrument is also able to perform high accurate surface roughness measurements, the profile roughness on the chipping surface was calculated. Figure 7 shows the results of this measurement.

4. Conclusions

This paper demonstrates the strength and the high potential of the presented focus variation measurement instrument for high accurate, repeatable cutting edge microgeometry measurements on an edge calibration tool. Moreover, it is shown that the measurement instrument can measure the complete 360° form of round tools with different dimension. We show the capability to measure micro drills with a major diameter of ~60 µm. An evaluation of geometry and surface roughness shows the high potential of the measurement instrument to perform a complete optical inspection of tools.

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