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FOCUS VARIATION – A NEW TECHNOLOGY FOR HIGH RESOLUTION OPTICAL 3D SURFACE METROLOGY

R. Danzl[1], F. Helmli[1] and S. Scherer[1]

[1]Alicona, Teslastraße 8, 8074, Grambach/Graz, Austria
reinhard.danzl@alicona.com

ABSTRACT

In recent years optical non-destructive methods for 3D surface metrology have become increasingly important in contrast to traditional tactile measurement techniques. Here, we present the operating principle and possible applications of the optical 3D measurement system "InfiniteFocus", which is based on the technology of Focus-Variation and used for quality assurance in the lab and in production. In contrast to traditional tactile methods it is able to perform 3D measurements without touching the surface, it measures whole areas instead of only surface profiles and delivers true color information in addition to the 3D data.
The technique of Focus-Variation combines the small depth of focus of an optical system with vertical scanning to provide topographical and color information from the variation of focus. The main characteristics of the system are that it delivers high resolution measurements of even complex surfaces, that it is able to measure surfaces with steep flanks up to 80°, with strongly varying reflection properties and greatly varying roughness. In addition to 3D and color information a repeatability measure is analytically estimated for each measurement point. Focus-Variation is used to perform high resolution 3D surface measurement for industrial quality assurance as well as research and development activities. Key applications are surface measurement and characterization in e.g. cutting tool industry, precision manufacturing, automotive industry, all kinds of materials science, corrosion and tribology, electronics, medical device development or paper industry. We demonstrate the capabilities of the system on a series of applications including wear analysis of cutting tools, the inspection of welding spots and different applications in the field of engineering and material science.

***Key words**:* metrology, 3D, optical, focus-variation, measurement.

1. Introduction

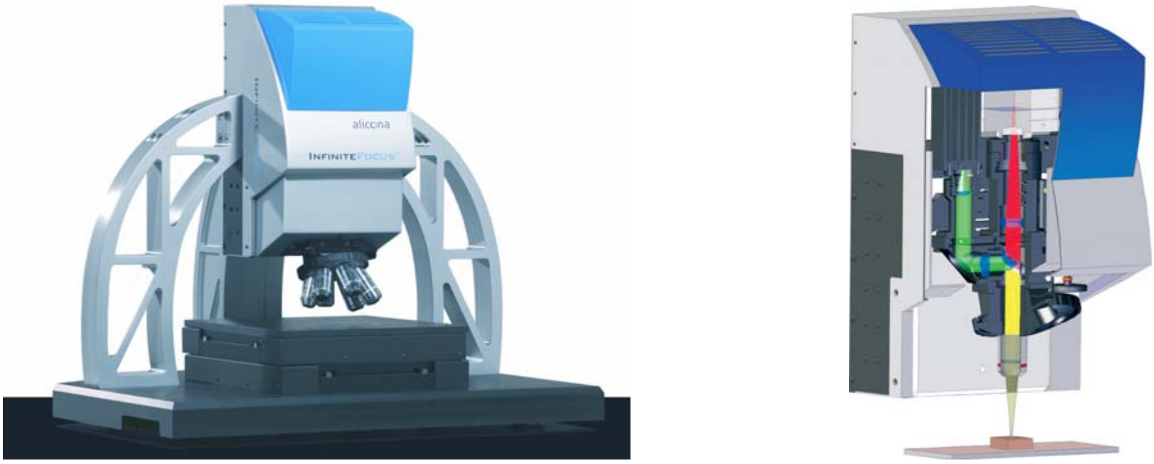
The 3D measurement of technical surfaces is a crucial part in checking and controlling the properties and the function of materials or engineering parts. While such measurements have been made using tactile devices for several decades, there has recently been a strong shift towards optical non-destructive 3D metrology devices [6]. Such devices have a series of advantages over tactiles ones. First they do not touch and damage the surface, second they are able to measure whole areas instead of only surface profiles and third they are typically much faster for detailed measurements of large areas.

Here we present the optical metrology device InfiniteFocus which is based on the Focus-Variation principle (Section 2) and offers a large range of different applications due to its special measurement principle. In contrast to other systems that are limited to few applications the InfiniteFocus device can be applied to different measurement tasks including roughness, form and wear measurement (Section 3).

2. 3D Measurement with Focus Variation

Focus-Variation [1] combines the small depth of focus of an optical system with vertical scanning to provide topographical and colour information from the variation of focus. In the following, the operating principle is demonstrated using the optical 3D measurement device InfiniteFocus (Fig. 1a), schematically shown in Fig. 1b. The main component of the system is a precision optic containing various lens systems that can be equipped with different objectives, allowing measurements with different resolution. With a beam splitting mirror, light emerging from a white light source is inserted into the optical path of the system and focused onto the specimen via the objective. Depending on the topography of the specimen, the light is reflected into several directions as soon as it hits the specimen via the objective. If the topography shows diffuse reflective properties, the light is reflected equally strong into each direction. In case of specular reflections, the light is scattered mainly into one direction. All rays emerging from the specimen and hitting the objective lens are bundled in the optics and gathered by a light sensitive sensor behind the beam splitting mirror. Due to the small depth of field of the optics only small regions of the object are sharply imaged. To perform a complete detection of the surface with full depth of field, the precision optic is moved vertically along the optical axis while continuously capturing data from the surface. This means that each region of the object is sharply focused. Algorithms convert the acquired sensor data into 3D information and a true colour image with full depth of field. This is achieved by analyzing the variation of focus along the vertical axis.

Using the 3D measurement device InfiniteFocus based on the operating principle of Focus-Variation, the following technical specifications emerge: The vertical resolution depends on the chosen objective and can be as low as 10nm. The vertical scan range depends on the working distance of the objective and ranges from 3.2 to 22mm. In contrast to conventional techniques, the vertical resolution is achieved regardless the scan height leading to a vertical resolution dynamic of 1: 430000. The XY range is determined by the used objective and typically ranges



(a) (b)

Fig. 1: (a) IFM G4 laboratory system (b) schematic visualization of the focus-variation technology. The small depth of focus of the optical system is used to extract depth information with registered true color.

from 0.14 x 0.1mm to 5 x 4 mm for a single measurement. By using special algorithms and a motorized XY stage the XY range can be exceeded up to 100 x 100mm.

In contrast to other optical techniques that are limited to coaxial illumination, the max. measurable slope angle is not only dependent on the numerical aperture of the objective. Focus-Variation can be used with a large range of different illumination sources (such as a ring light) which allows the measurement of slope angles exceeding 80°. Basically, Focus-Variation is applicable to surfaces with a large range of different optical reflectance values. As the optical technique is very flexible in terms of using light, typical limitations such as measuring surfaces with strongly varying reflection properties even within the same field of view can be avoided. Specimen can vary from shiny to diffuse reflecting, from homogeneous to compound material and from smooth to rough surface properties. Focus-Variation overcomes the aspect of limited measurement capabilities in terms of reflectance by a combination of modulated illumination, controlling the sensor parameters and integrated polarization. Modulated illumination means that the illumination intensity is not constant, but varying. The complex variation of the intensity can be generated by a signal generator. Through the constantly changing intensity far more information is gathered from the specimens´ surface.

In addition to the scanned height data, Focus-Variation also delivers a colour image with full depth of field which is registered to the 3D points. This provides an optical colour image which eases measurements as far as the identification and localization of measurement fields or distinctive surface features are concerned. The visual correlation between the optical colour image of the specimens´ surface and its depth information are often linked to each other and are therefore an essential aspect of meaningful 3D measurement.

Since the described technique relies on analyzing the variation of focus it is only applicable to surfaces where the focus varies sufficiently during the vertical scanning process. Surfaces not fulfilling this requirement such as transparent specimen or components with only a small local roughness are hardly measurable. Typically, Focus-Variation delivers repeatable measurement results for surfaces with a local Ra of 10nm at a lc of 2µm.

Focus-Variation is used to perform high resolution 3D surface measurement for industrial quality assurance as well as research and development activities. Key applications are surface analysis and characterization in e.g. cutting tool industry, precision manufacturing, automotive industry, all kinds of materials science, corrosion and tribology, electronics, medical device development or paper and print industry [4]. Due to its´ technical specifications the Focus-Variation technique is used for form and roughness measurements.

3. Applications

In the following we provide several applications that are realised with Focus-Variation. The first application is the roughness measurement of newly developed roughness standards with sinusoidal profiles. Hereby we particularly focus on the comparision of the results between the InfiniteFocus device and a traditional tactile system. In the second application we focus on form measurement, in particular the measurement of hemi-spherical calottes that are part of a special calibration target. Another provided application is the wear measurement of milling-cutters. This application demonstrates the ability of the system to measure surfaces with steep flanks and to calculate the difference between two measurements. Finally we provide a typical engineering example, namely the measurement and inspection of welding spots which is challenging due to the difficult reflance characteristics of welding spots.

3.1 Roughness Measurement on a newly developed Roughness Standard

The measurement of surface roughness is one of the most common and important ways to judge the quality of a technical surface. In order to verify whether a metrology device is able to measure certain types of roughness accurately, various roughness standards with calibrated roughness values are available.

In the following we describe the process of performing a roughness measurement comparison between InfiniteFocus and a tactile instrument on a newly developed roughness standard. After a review of the main problems that may occur when making such a comparison, we describe the roughness standard and provide the results of the comparison.

The main problem of contact stylus instruments in the context of roughness measurement is that the form of the contact stylus tip has a smoothing effect on the surface profile and can therefore influences the measurement result. Another error source of contact stylus instruments is that the stylus tip may modify the surface if the material is not hard enough. (Fig. 2) Sometimes the stylus tip is not traced along a straight line but may be deflected, e.g. when composite materials consisting of very smooth and very hard components are measured.

The main problem of optical instruments is that most existing roughness standards are rather smooth and can hardly be measured with several optical instruments. Therefore a new roughness standard has been developed which contains a certain amount of nano-scale roughness and which is well-measurable with optical devices such as InfiniteFocus.

The roughness standard used for the comparison is a precision roughness specimen [5] having a regular periodic sinusoidal profile with a nominal peak-to-peak spacing Sm = 50 µm, a peak-to-valley height Pt = 1.5 µm and a resulting nominal Ra = 0.5 µm. Starting from the precision diamond-turned master specimen, various electroformed nickel replicas were produced, which are all faithful copies of the original and of each other. The sloping flanks between the peaks and valleys of the sinusoidal roughness profile, however, are smooth and shiny; and in order to introduce some nano-roughness onto these surfaces, the nickel specimens were etched with a dilute acid solution for varying lengths of time. The roughness standard is shown in Fig. 3a whereas a schematic height profile is provided in Fig. 3b showing a schematic height profile of the standard, the nano-roughness and the meaning of the parameters Sm and Pt. The latter diagram illustrates both the overall sinusoidal shape formed by the machining process, and also the superimposed random nano-roughness which is the result of the acid etch. Note that the nano-roughness is relatively small in comparison to the sinusoidal roughness, so that the overall Ra values measured on the etched surface will be very close (within ~1%) to those measured on the unetched sinusoidal surface.

A 3D measurement of the standard is provided in Fig. 4b together with a sharp measured image in Fig. 4a. In order to calculate the roughness of the surface, a surface profile has been extracted along a horizontal profile path as shown in Fig. 5. The measured surface profile is visualized at the bottom of Fig. 5 showing the regular sinusoidal shape of the surface. The measurement can be performed within the graphical user interface of the InfiniteFocus system that allows easy change of measurement positions, cutoff values and switching between primary, roughness and waviness profiles.

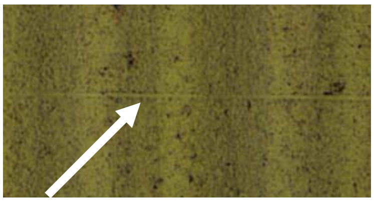
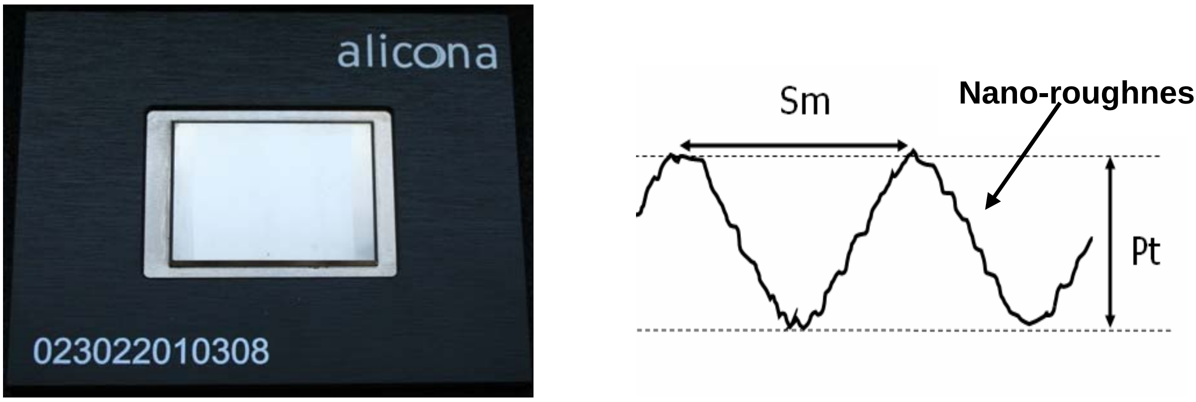
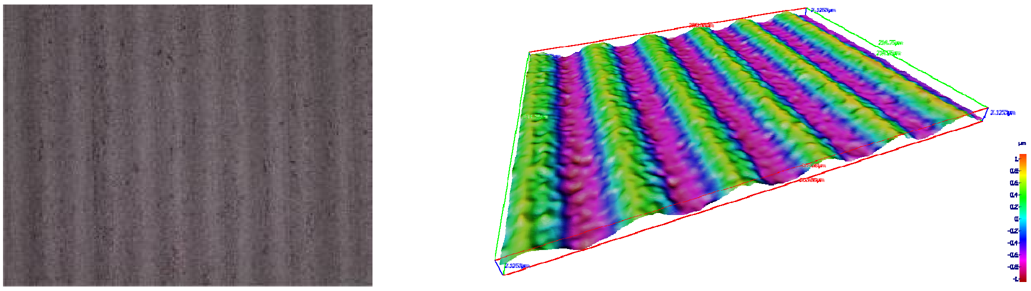


Fig. 2: An optical color image of a sinusoidal roughness standard (Ra = 500nm) obtained by the InfiniteFocus device. The image shows the horizontal trace of a contact stylus instrument that has been used for reference roughness measurements.



(a) (b)

Fig. 3: (a) Roughness standard, used for the comparison (b) Schematic height profile of the roughness standard showing the sinusoidal structure, the nano-roughness and the meaning of the parameters Sm and Pt.



(a) (b)

Fig. 4: (a) Sharp color image of the roughness standard obtained by InfiniteFocus. (b) 3D dataset of the roughness standard obtained by InfiniteFocus within a single field of view. The 3D dataset is visualized in pseudo colors and shows the regular structure of the sinusoidal standard as well as the small scale nano-roughness.

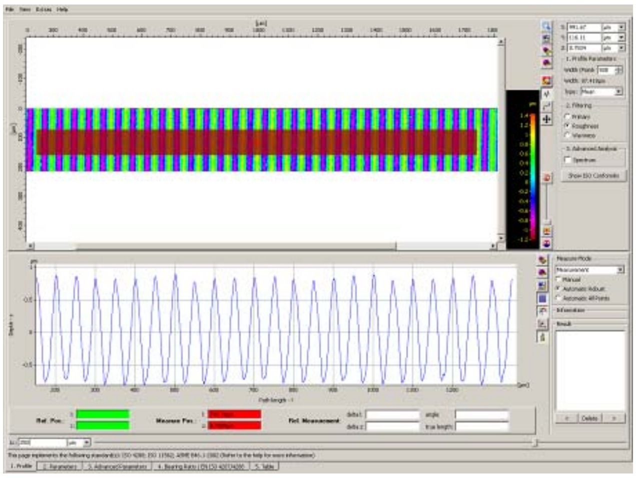


Fig. 5: Extracted surface profile of the sinusoidal roughness standard.

In order to compare the roughness measurements of the tactile and the optical system, the following procedure has been used. First, the roughness standard has been measured by the tactile instrument at 30 different positions arranged in three straight rows of ten each. This coverage of the whole measuring area serves as a check upon the uniformity of the roughness values from place to place. For the InfiniteFocus device only a single measurement position has been used, where roughness measurements have been repeated 25 times. This allowed to compare the measurement results to those of the tactile system and to calculate the repeatability of the measurements of the optical system.

The results of this measurement row are graphically visualized in Fig. 4, showing the different measurement results as well as a Gaussian distribution curve depending on the repeatability of the measurements. It should be noted that the measurements of the tactile instrument have been performed at 30 different positions, so that the standard deviation contains the variability of the measurement device and the variability of the roughness standard. In contrast to this, the measurements of InfiniteFocus have all been performed at the same position. As a result the standard deviation of InfiniteFocus only contains the variability of the measurement device. Overall both measurements are very similar to each other showing the possibility of InfiniteFocus to perform roughness measurements that are comparable to traditional tactile devices.

In addition to profile based roughness measurements the InfiniteFocus system is equipped with an area-based roughness module that allows the calculation of area-based roughness measurements conform to a draft of an ISO standard on area-based roughness measurement. In comparison to traditional profile based roughness measurement this allows to calculate a much larger range of different surface texture parameters including amplitude parameters, volume parameters or the fractal dimension of the surface. The big advantage of area based roughness measurement is that the results get usually more representative and repeatable due to the larger amount of data used for calculation. This module also allows the subtraction of different forms (spherical, cylindrical), two-dimensional Gaussian filtering and the filtration of measurement points with bad quality.

Table 1 Comparison of the measurements performed by the tactile instrument and by the InfiniteFocus system.

	Tactile Instrument	InfiniteFocus
# Measurements	30	25
Mean Ra	503.5nm	515.26nm
Std Ra	4.95nm	0.81nm

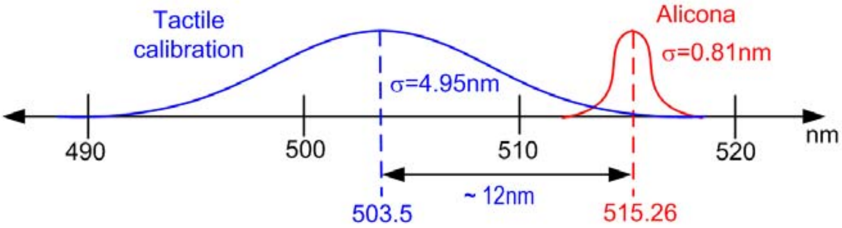
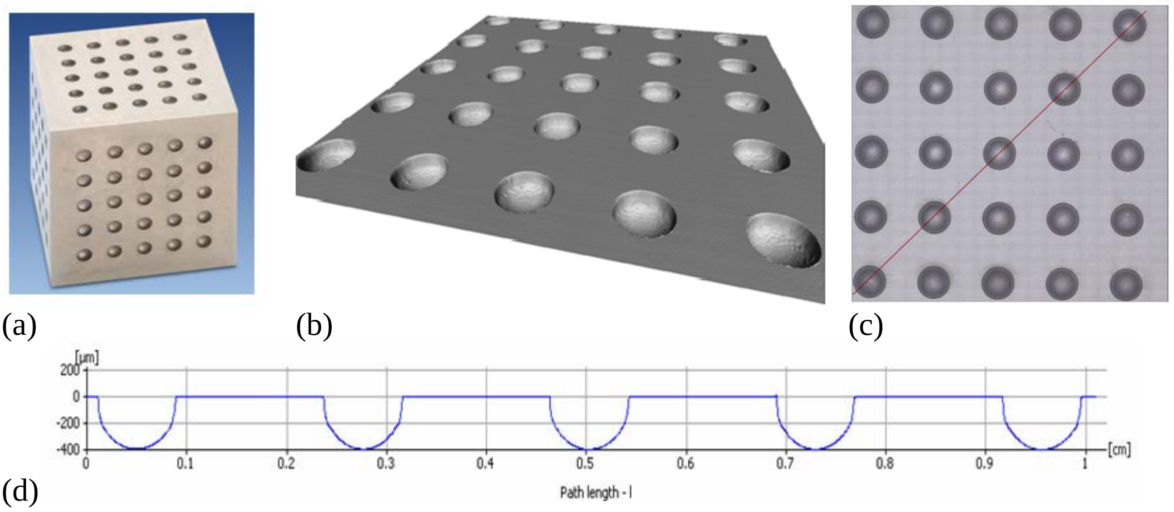


Fig. 4: Visualisation of the roughness measurements of Alicona and the tactile instrument showing the mean Ra values and the standard deviations of the measurements.

3.2 *Form Measurement of Hemi-Spherical Calottes*

A big advantage of the InfiniteFocus device is its ability to not only measure the roughness but also the form of technical surfaces. In the following we demonstrate the ability of InfiniteFocus to measure the form of hemisperical calottes on a calibration standard developed by the PTB. This calibration standard has the form of a cube with dimensions 10x10x10mm with 25 hemi-spherical calottes with a nominal radius of 400µm on three faces (Fig. 5a).



(a) (b) (c)

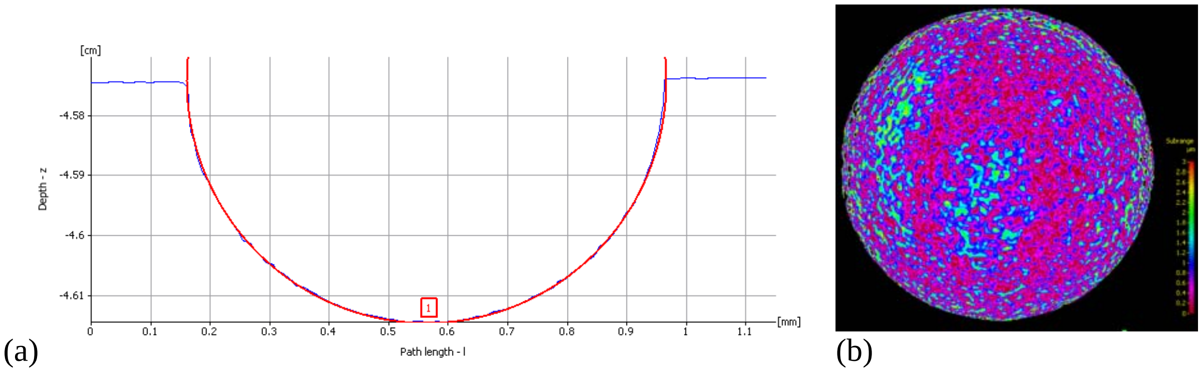
(d)

Fig. 5: (a) The PTB calibration standard (b) 3D dataset of the measured calibration standard; (c) measured sharp true colour image with profile path; (d) extracted height profile.

Each side of the standard is rather large (10mm x 10mm) which can only be measured with devices that allow sufficiently large measurement areas. Second, the standard has to be measured with sufficient vertical resolution and accuracy to provide reliable data for the sphere fitting process. Third, the device has to be able to measure even steep surface flanks since the calottes consist of surface patches with angles up to 90°.

In the following we provide measurements of this standard using the InfiniteFocus device, that meets all the above mentioned requirements. In Fig. 5 the measurement results are demonstrated for one side of the calibration standard. In Fig. 5b a 3D dataset is shown which covers all 25 calottes on one side of the cube. In Fig. 5c the measured sharp colour image is provided. Into this image a 2D profile path has been drawn (red) along which a surface profile has been extracted as shown in Fig. 5d. Fig. 6a provides a detailed surface profile where a circle has been fitted into the measured points. The fitted circle and the measured points show very good correspondence even at the steep flanks. In Fig. 6b a difference height dataset is provided that shows the absolute differences between measured points and a sphere fitted in the least-squares sense. The pink and red colour represents small deviations < 0.8µm whereas the other colours represent deviations between 0.8µm and 3µm.

In order to evaluate the repeatability of the system we have measured the radii of a sphere 30 times in a row. The standard deviation sigma of the measurements is ~15nm which is very small if one considers the sphere radius of 400µm. The standard deviation can be converted into a confidence interval [mean -2*sigma, mean + 2*sigma] which is ~60nm and covers about 95% of all measurement results.



(a) (b)

Fig. 6: (a) Height profile of one calotte with fitted circle; (b) absolute difference height map between measured and fitted sphere.

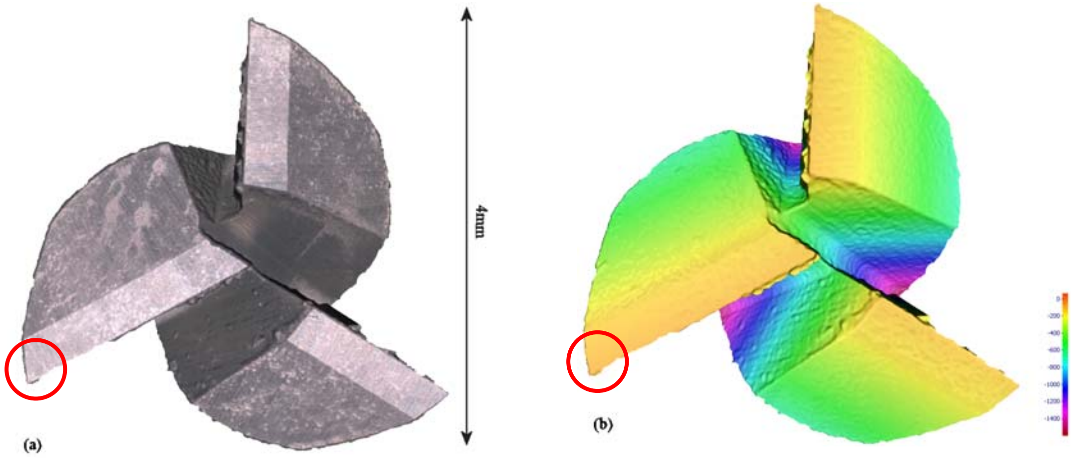


Fig. 7: 3D datasets of a milling cutter measured by InfiniteFocus. The parts that have been investigated in detail are marked with red circles. (a) 3D dataset with superimposed true color image. (b) 3D dataset with pseudo colors where each color represents a different height.

The combination of accurate measurements, robust sphere fitting algorithms and automated methods makes the proposed optical device ideally suited for the 3D measurement of the presented calibration target. More information on the measurement of these samples can be found in [2].

3.3 Wear Measurement of Cutting Tools

In order to judge the quality of cutting tools it is necessary to measure their geometry and wear during their use in the industrial process. This allows taking measures to improve the quality and durability of the tools as well as to increase the machining speed. In the following we demonstrate how the 3D metrology device InfiniteFocus can be used for such complex geometry and wear measurements.

We have measured the wear on corners of a milling cutter measured by InfiniteFocus (Fig. 7). In contrast to many other 3D measurement devices InfiniteFocus is able to measure steep flanks. Additionally it does not only deliver 3D data but also perfectly registered true color information ad shown in Fig. 7a.

First 3D datasets of the corner (red circle in Fig. 7) have been measured before and after usage. Afterwards the difference between the two 3D datasets has been calculated which contains the worn material. In order to assure that the difference is calculated from corresponding surface regions, the two 3D datasets have been registered to each other before difference calculation.

In Fig. 8a a 3D dataset of the original corner is provided, whereas Fig. 8b contains a 3D dataset of the used corner. Both 3D datasets have been overlaid with the true color image measured by InfiniteFocus. This allows a classification into original regions (dark) and worn regions (bright). After the two 3D datasets have been registered to each other, a difference height dataset has been calculated (Fig. 8c) which allows the quantification of the worn volume (~601400µm^3). Another possibility to measure the amount of the worn volume is to extract height profiles of the original and the worn part and to overlay them (Fig. 8d) in a single diagram. This allows a good visualization of regions where much and regions where little material has been removed.

This combination of high accurate 3D measurement over large areas even at steep edges, as well as robust measurement functions makes the device ideally suited for the measurement of various cutting, milling and drilling tools. Additional measurements of milling cutters are provided in [3].

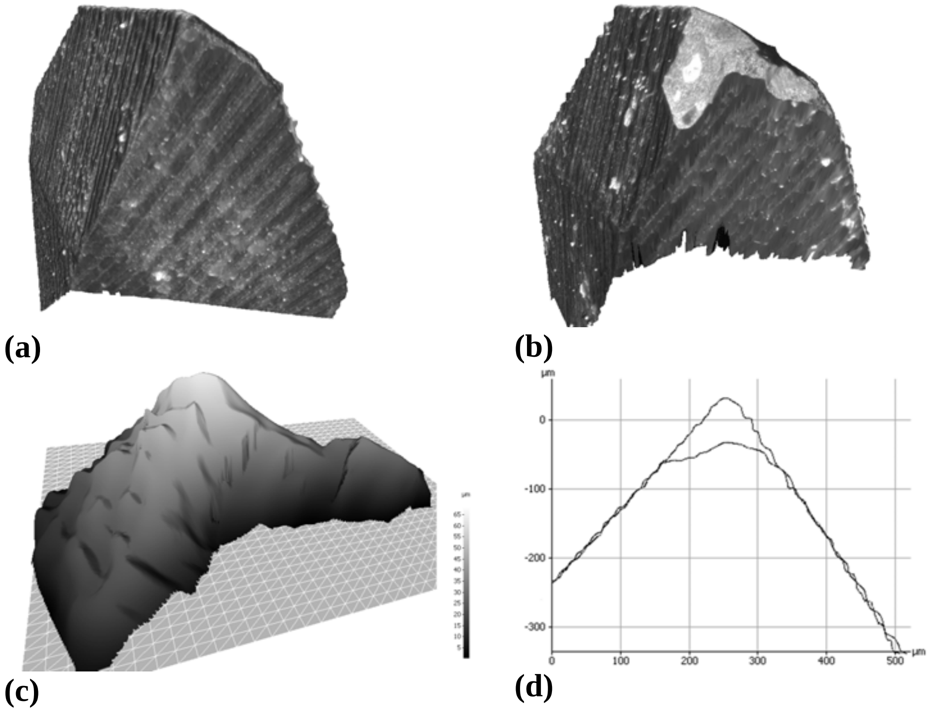


Fig. 8 : (a) Unused cutting edge (b) Used cutting edge (c) Difference volume of used and unused cutting edge (d) Profiles of used and unused cutting edge

3.4 Inspection of Welding Spots

Laser beam welding is commonly used because of high-strength welding assembly, the small weld seam and the high qualitative weld seams without brittle occurrence. The check and evaluation respectively the automatic classification of welding spots into parts that are ok and parts that are not ok during the production saves expensive and time consuming rework. The automatic classification is achieved by robust measurements of steep flanks and complex reflections which are characteristic surface features of welding spots. In order to create these two classes a variety of parameters is measured in 3D in combination with color information. The combination of high resolution measurement data with the accordingly measured registered true color information is an important requirement. Due to this fact the localization and the topographic acquisition of high temperature oxidation can be realized. The measurement opportunities which are enabled by the Focus-Variation contribute essentially to the optimization of welding procedures. In Fig. 9 the 3D dataset of a measured welding spot is displayed. Fig. 10 shows the dataset and the measured surface profile.

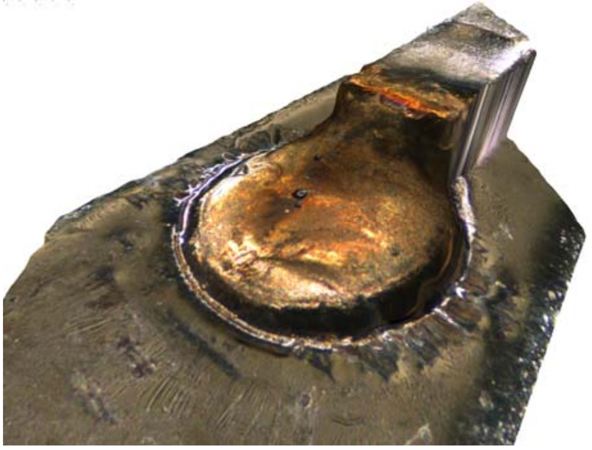
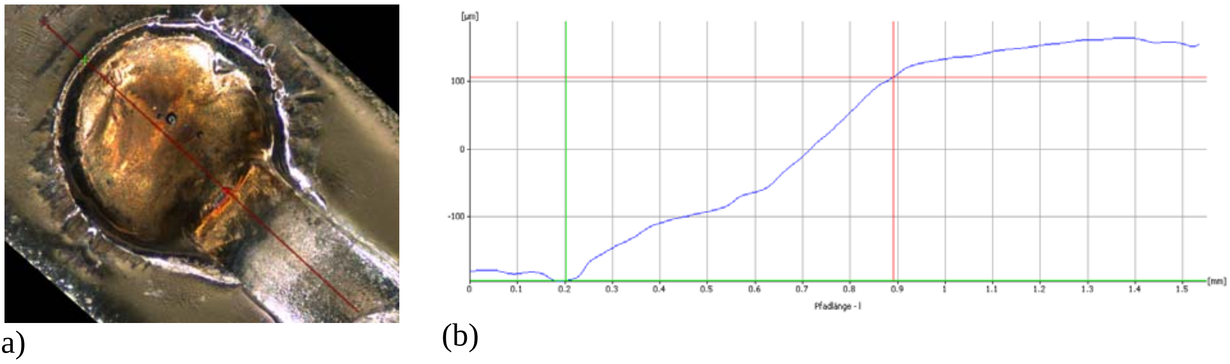


Fig. 9: The robust measurement of surfaces with steep flanks and extreme reflections make the Infinite Focus to a very suitable tool for welding spot checks.



(a) (b)

Fig. 10: (a) Optical colour image with overlaid profile path. (b) Extracted surface profile with two measurement positions (green and red). The surface profile can be used to decide whether the welding spot is ok or not ok.

5. Conclusions

We have described the optical metrology device InfiniteFocus which is based on Focus-Variation and shown its use for a wide range of different applications including form, roughness and wear measurements. Roughness measurements on a newly developed roughness standard have provided very similar results to traditional tactile devices with the benefit that the surface is not damaged. Form measurements on calibration standards with hemi-spherical calottes demonstrate the high repeatability of the system whereas wear measurements on milling cutters have shown the ability to measure complex surfaces and parameters. Finally we have provided a typical industrial application, namely the inspection and measurement of welding spots.

6. References

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