

Optical 3D Digitization and Coordinate Measurement of Parts by Means of DLP Based Projected Fringe Measuring Technology

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1 Introduction

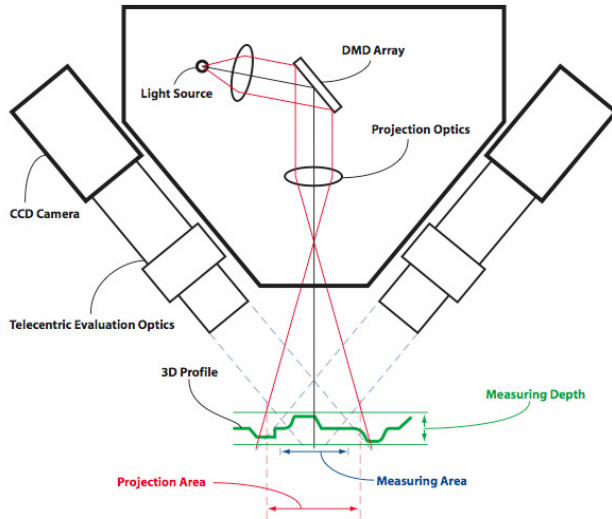
Coordinate measuring machines (CMM's) are a basic requirement for any industrial manufacturing facility conforming to the specifications of drawings and standards. Accuracy needs to be observed, verified and certified with respect to a comprehensive set of standardization rules. Highly precise CMM's have costly requirements, such as vibration isolation, environmental temperature stabilization, and a long measurement time. An ideal CMM would function without these drawbacks so that the same measuring performance could be taken directly to the production line and used by manufacturing personnel. These shortcomings of CMM's don't have any foreseeable solutions for the near future. But there is economic motivation to demand an easy to use CMM without the requirements of environment control and long measurement times for the acquisition of accurate 3D data. CAD based manufacturing takes its measures and tolerances from CAD data. A 3D measuring device that could, within a few minutes, provide several million measuring points and compare that data to CAD data as a nominal/actual value comparison on site by manufacturing personnel would meet the demands of industry. Fringe projection technology, with its precision and flexibility in applications, can meet the idealized requirements of industrial manufacturing. This technology has established itself as fast industrial 3D measurement method in recent years. Advanced 3D measurement software is capable of comparing CAD data to measurement data as well as fast nominal/actual data comparison in three-dimensional space. These 3D measurement comparisons clearly indicate deviations between nominal and actual measurements.

2 Fringe projection as an optical 3D measurement technique

Fringe projection as an optical measurement technique combines the advantages of triangulation techniques and the real time interferometry. With these two techniques, large objects with rough surfaces can be measured fast and accurately. This is possible because the fringe projection works by projecting a sequence of equidistant fringe projection patterns with a nearly \cos^2 -shaped intensity distribution on the scanned surface as compared to the triangulation technique, which projects a single point of light or a light-section. Two cameras, angled to the direction of the projection, observe these fringe projection patterns. Fig. 1 shows the functional basics of such a fringe projection measurement setup. The 3D measurements result from the deflection of the projected parallel fringe pattern on the curved surface as inspected by the two cameras due to triangulation. The projected fringe patterns are, as mentioned before, nearly \cos^2 -shaped, and thus they can be perceived as interferograms and they can be evaluated by algorithms for phase analysis, just as they are used for real time interferometry techniques. This phase measuring fringe projection technique enables a much higher resolution of the profile and accuracy of the measurement. Fringe projection also allows 3D measurements without moving the target object or the sensor, as conventional triangulation measurement techniques would require.

A fast projection of the fringe pattern is essential for a precise measurement and a good use of the fringe projection, which requires an intensity distribution as much alike the distribution of wave-optically generated interferograms as possible. Both of these requirements are supported by the use of micro-mirror displays, as developed using DLP technology by Texas Instruments/USA and globally used for light projection in diverse applications [3]. Texas Instrument's micro-mirror projectors facilitate high contrast and strong light and they feature separately and digitally controlled mirrors with a maximum size of 1024 x 768. This makes it possible to measure black as well as par-

tially reflective surfaces, such as tools of precision forged gearwheels, as shown in the following examples of use.



The subject of evaluation when employing the fringe projection technique is the registration and evaluation of the fringe patterns and their distribution, which result from the position of the cameras and the intersection of the fringes, projected in parallels, and the curved surface. These fringe patterns represent a direct 3D image of the surface, and the degree of deflection and the density of the fringe distribution respectively allow for a qualitative evaluation of the surface shape of the measurement object.

Fig. 1 Principle of a fringe projection setup including two cameras and a projector

3 Fringe projection based coordinate measurement technique

Coordinate measurement machines (CMM) in the industrial production are an indispensable premise for a quality assurance of the produced parts, which conforms to the given standards. At the present time tactile CMM's are common, which are mainly used in special measuring laboratories. Optical and tactile systems are combined to form so called multi-sensor CMM's. They are either equipped with point and/or line based laser scanning systems or auto-focus sensors.

Within a few seconds fringe projection CMM's supply plane 3D datasets with up to several millions of single measurement points. The part to be measured can be scanned from several directions, each scan resulting in a so-called single view. These single views are merged using software in order to obtain a complete 3D dataset of the measured part. This 3D dataset can be used for a 3D measurement as well as for a CAD-based nominal/actual value comparison using the appropriate measuring and evaluation software.

3.1 Optical 3D coordinate measurement machine TopoCAM

The optical measurement machine TopoCAM is a fringe projection based 3D coordinate measurement machine, which, as seen in Fig. 1, has a projector and two sideward oriented CCD cameras. Fig. 2 shows the design of this measurement machine. The standard version of this measurement machine carries at least three CNC linear axis, which can move the 3D sensor and/or the measured part in the x, y and z direction. If required it is possible to install a measuring panning or rotation axis in addition to the linear axis. Tab. 1 summarizes the essential parameters of the measurement machine TopoCAM. The part to be measured is placed in a simple and normally universal adapter. At the push of a button a specific measurement program starts, which controls the measurement, the necessary movements of the axis, and the assembly of the single scatter plots or single views to form a complete 3D scatter plot. The result of the measurement will include a 3D dataset and a



Fig. 2 Implementation of the optical 3D coordinate measurement machine TopoCAM

complete solid of the measured part respectively, and if need be it will directly, without manual intervention conduct a comparison with the related CAD model.

The time requirement for the measurement of more than two million measurement points and the output of the measurement and the test result based on the mentioned nominal/actual value comparison adds up to less than one minute. Due to the robustness of the measurement system and its simple handling these measurements can be conducted on-site during the production process and directly by the production personnel. There is no need for special knowledge about measurement techniques, in particular regarding the handling of optical 3D measurement systems. The required accuracy of the measurement can be adjusted according to the current constructive necessities. Basically the relation of the accuracy of the optical measurement system and the component tolerance at hand is 1/10.

Tab. 1 Main parameters of the projected fringe based 3D coordinate measuring machine TopoCAM

Sensor volume	[mm]	40 x 30 x 30		
Measuring volume	[mm]	240x230x230	290x270x250	380x350x350
MPE_{PF}	[mm]	0.007	0.008	0.012
MPE_{PS}	[mm]	0.005	0.010	0.010
MPE_{SD}	[mm]	0.004	0.007	0.012
MPE_{FD}	[mm]	0.004	0.005	0.008
MPE_E	[mm]	0.0025+L/100	0.01 + L/100	0.015+L/100

3.2 Software package TopoXenios

In many cases and especially when dealing with dimension controls in the industrial production a nominal/actual value comparison of the 3D dataset or the solid and the related CAD dataset or a master dataset might be sufficient for a “good”-“bad” evaluation of a produced part. Fig. 3 gives an example of such a contour control of a turbine vane. Fig. 3 shows a so-called differential image of the measured turbine vane and its CAD model. The colors indicate the extent of the form deviation, which can also be numerically displayed in a table.

On the one hand the comparison of the CAD dataset and the optically measured 3D dataset as shown in Fig. 3 is not sufficient for a complex 3D coordinate measurement as usually conducted when using common CMM's. On the other hand the currently available software packages, e. g. the package Calypso as distributed by Carl Zeiss, are not designed for the need of optical 3D measurement techniques and are not able to cope with the efficient evaluation of 3D datasets containing several millions of single measurement points.

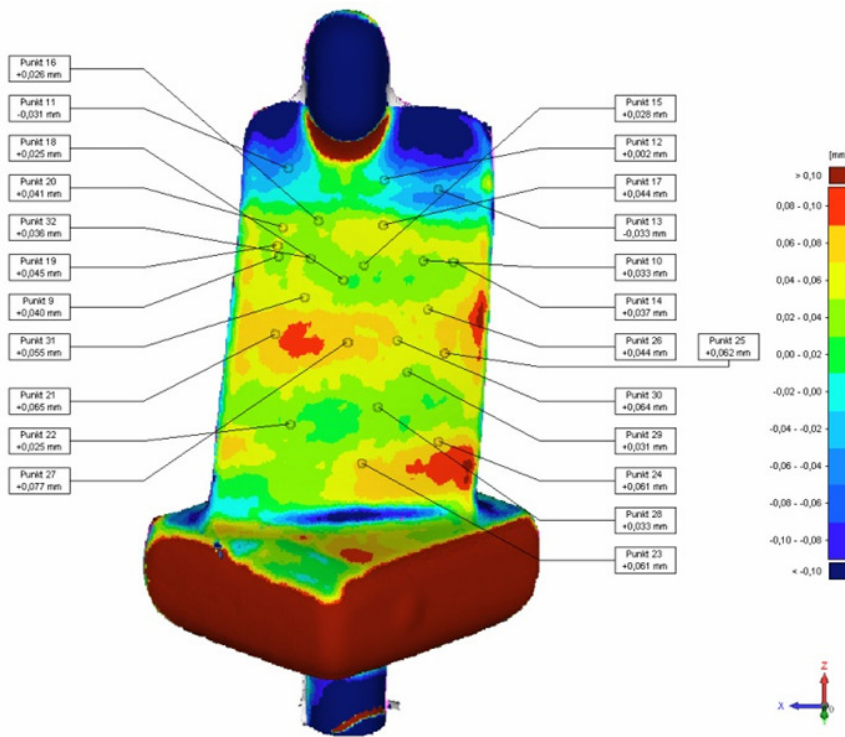


Fig. 3 CAD-based nominal/actual value comparison of a turbine vane

The numerical evaluation of scanned contours or surfaces is basically limited to regular geometric characteristics such as cylinder, plane, straight line, sphere and circle. However modern production techniques more and more support creative design, which is no further bound to regular shapes.

In order to process 3D datasets containing several millions of measurement points for the purpose of the 3D coordinate measurement technique, the GFM developed the software package TopoXenios.

It supports the recording of the measurement as well as the extensive evaluation, including:

- the determination of the alignment of the measurement datasets using standardized geometries

- the generation of measurement and combination strategies using color code and text visualization
- the registration of all measurement features in a tree structure
- the calculation and combination of all standardized and free geometries as well as contour, position and alignment of the tool
- setting defined 2D traces in local coordinates of the measurement data set and interactive dimensioning
- generating graphical and numerical measurement protocols as well as protocols containing all testing characteristics, labels, tolerances and deviations.

At the same time TopoXenios enables the automation of the complete measurement routine, from the measurement data acquisition to the evaluation and if necessary a CAD based actual/nominal value comparison; this is of high importance for the use in the production and in production related areas respectively.

3.3 Calibration and accuracy of measurement

When calibrating the measurement volume of a fringe projection 3D coordinate measurement machine, a specially designed calibration strategy and specifically certified calibration probes for the x and y plane as well as for the z direction are used. In addition to the calibration of the measurement volume it is necessary to adjust to existing deviations of the optical projection and recording equipment and to state these corrections of the evaluation program in a so called correction matrix [5].

The certification of a proper calibration state of the fringe projection coordinate measurement machine is conducted in accordance with the VDI/VDE guideline 2634, which was developed especially for planar optical coordinate measurement machines [1]. Afterwards, as shown in Fig. 4, a barbell formed specimen is placed on defined measurement positions of the sensor's measurement volume and each distance to the sphere of the barbell is determined. The size of the barbell respec-

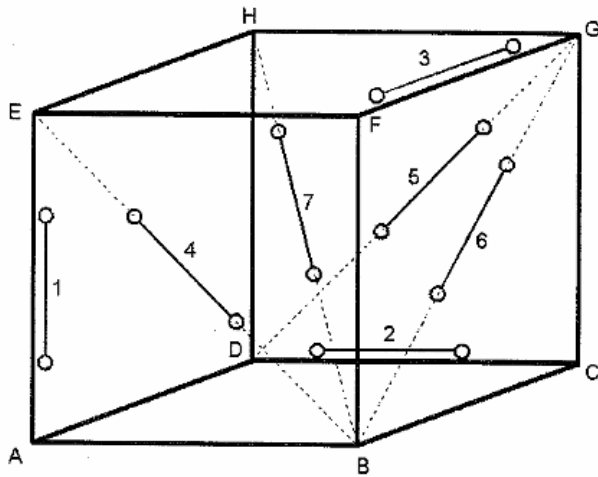


Fig. 4 Control of the calibration state of a planar optical CMM according to VDI/VDE 2634 [1]

tively the diameter of the sphere depends on the underlying measurement volume of the sensor and it is defined in the cited guideline.

Fig. 5 shows the barbell according to VDI/VDE 2634 for the TopoCAM measurement volume of the size 40 mm x 30 mm x 30 mm, as it is used for certifying the proper calibration state for this kind of measurement machine. Fig. 6 displays a barbell composed from six single views. Tab. 2 summarizes the results of ten single measurements of the barbell on the measurement volume.

These results indicate an accuracy of measurement of $2.5 \mu\text{m} + L/100$, which is a satisfying value for a planar tactile optical CMM. Thus the use of this fringe projection 3D CMM is guaranteed regarding essential technical applications.

Tab. 2 Results of the measurement of the probe according to VDI/VDE 2634 (calibrated radius: 16.795 mm)

Single measurement	1	2	3	4	5	6	7	8	9	10	X
Measurements [μm]	16.7985	16.7960	16,7937	16.7946	16.7953	16.7950	16.7960	16.7940	16.7955	16.795	0

4 Examples of use

4.1 Measurement of an insert

The manufacturing accuracy of cutting inserts, like all other cutting tools, must adhere to strict dimensional requirements. Dimensional requirements have to be assured during the manufacturing process as well as during practical use. Currently, either mechanical tactile or optical measurement techniques are used for the measurement of tools and cutting inserts. Normally these measurement techniques generate single point measurements or profiles. A new concept for the total 3D measurement of tools and inserts is the use of the 3D measurement machine TopoCAM in combination with the software package TopoXenios. This new concept is based on the approach of measuring several single views of the whole tool or cutting insert and subsequently evaluating the dimensions or conducting a nominal/actual value comparison by the use of the software package TopoXenios. The following paragraphs deal with an example procedure of measuring the complete 3D geometry of a cutting insert and the succeeding evaluation of the measured 3D scatter plot.

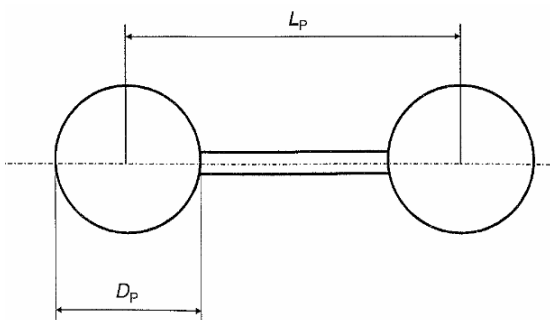


Fig. 5 Measurement probe according to the standard VDI/VDE-2634 [1]

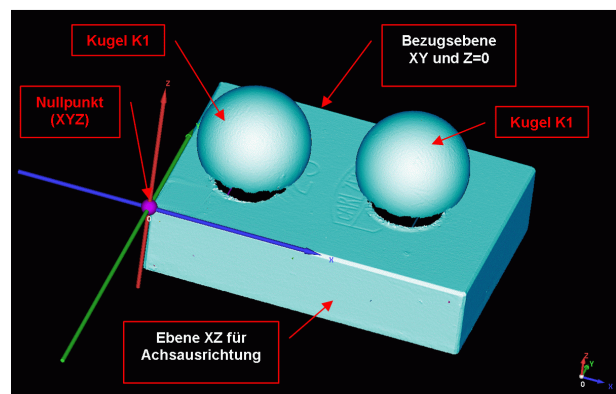


Fig. 6 3D scatter plot of the measurement probe

4.1.1 Geometry scan

A version of TopoCAM with a 40 mm x 30 mm x 30 mm sized measurement volume is used for the geometry scan of the cutting insert. The parameters stated in tab. 1 indicate an accuracy of measurement of $0.0025 + L/100$ for this measurement volume, which is equal to the accuracy of a mechanical tactile CMM and which is adequate for this function.

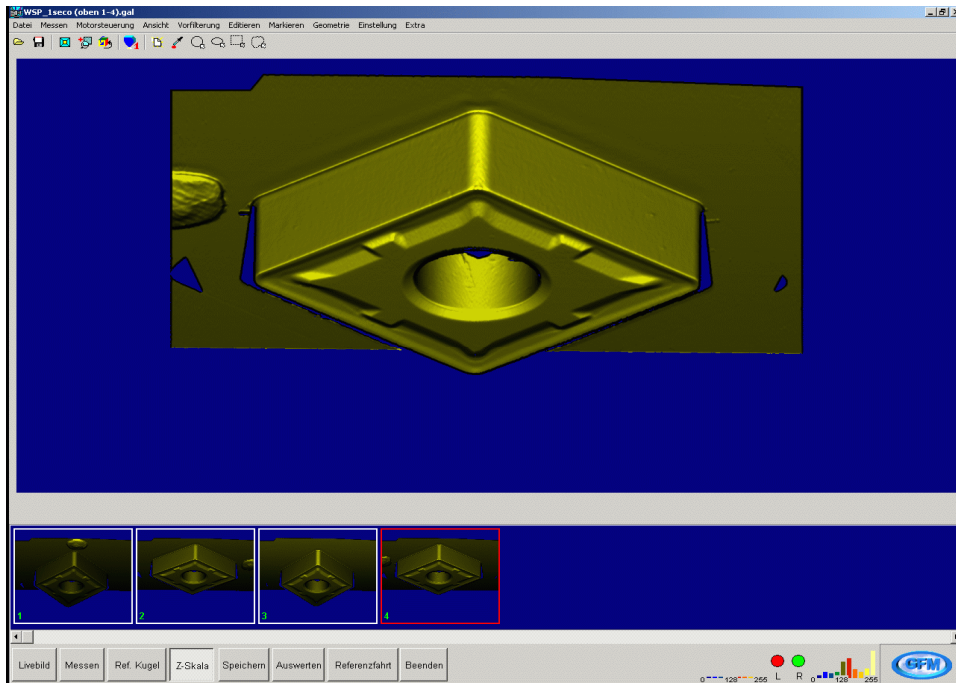


Fig. 7 3D measurement data scan (3D-Messdatenaufnahme) of a cutting insert using TopoCAM

During the measurement procedure, the cutting insert is positioned on a precision table inside the measurement volume of the TopoCAM. A computer controls the measurement table so individual measurement positions may be viewed. At each position a 3D scatter plot of the currently visible area of the cutting insert is recorded. After the recording the single plots are automatically combined to form a complete scatter plot or a solid volume model, which can then be used for the future analysis of the measurement. Fig. 7 represents the graphic resulting from the described measurement process.

The upper part of the figure shows the combined 3D scatter plot, the lower part displays four single views. TopoXenios is used for scanning the 3D scatter plot or solid of the cutting insert, shown in the upper section, and then allows for a CAD nominal/actual value comparison. TopoXenios provides the data for further evaluations as shown in Fig. 8. The displayed data already contains the coordinate system of the cutting insert as determined by TopoXenios.

4.1.2 Evaluation

The metrological evaluation of the measured cutting insert, as shown in Fig. 8, can be supported by several tools of the software package TopoXenios.

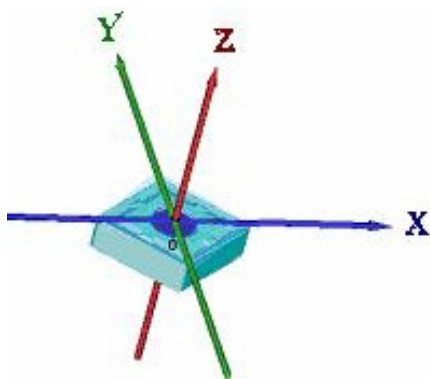


Fig. 8 Optically measured 3D data of an insert

These tools either assist in the measurement, allow the direct dimensioning of the 3D scatter plot or the dimensioning of defined section planes, which can then be extracted in form of graph lines and can be used for measuring the graph. This procedure is displayed in Fig. 9 and Fig. 10. The section plane, as to be seen in Fig. 9, refers to a given plane. The section plane is then redisplayed as a single plane with dimensions, which are generated using the dimensioning tool of TopoXenios, cp. Fig. 10. That way the dimensions of measured 3D profiles of a tool or a cutting insert can be determined and numerous single planar sketches can be generated.

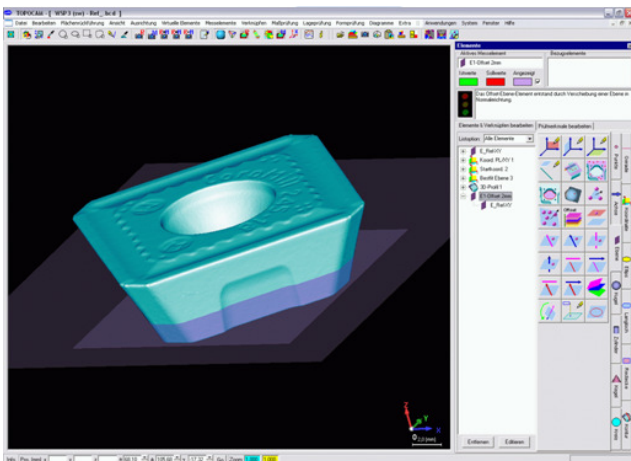


Fig. 9 Selection of section planes for dimensioning

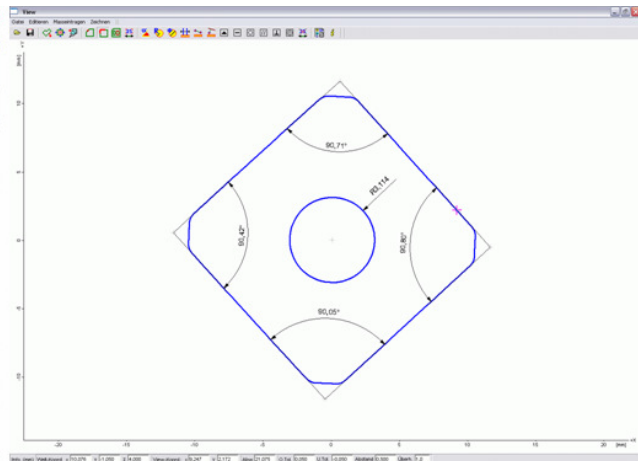


Fig. 10 Dimensioning the extracted section

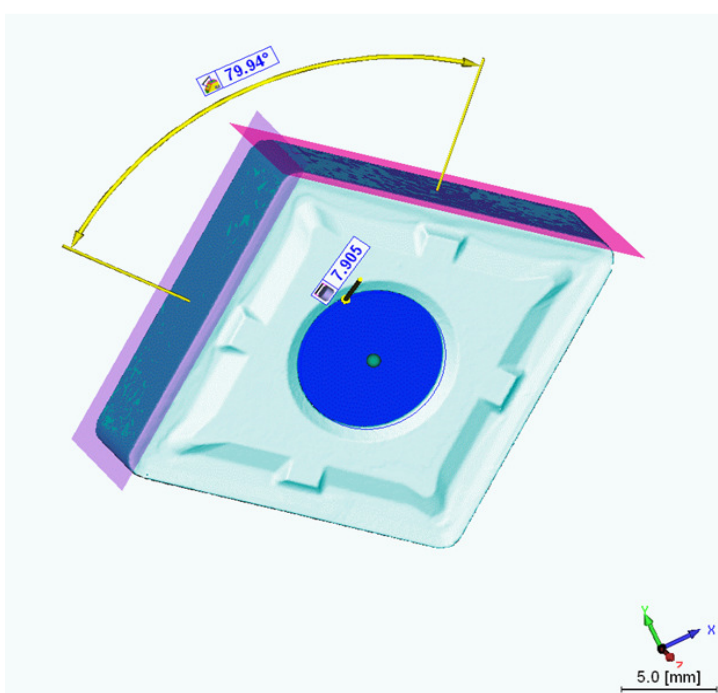


Fig. 11 3D dimensioning of the measured solid of an insert

As the optical 3D measurement machine TopoCAM generates a complete 3D scatter plot or a solid of the cutting insert, it lends itself to directly measure the 3D scatter plot and thus conduct a 3D evaluation. Fig. 11 represents this new possibility for a 3D evaluation on the measured cutting insert as it is made possible by the TopoXenios software. Compared to the common 3D coordinate measurement techniques, which support this evaluation method in a similar way, the fringe projection optical 3D coordinate measurement technique makes it possible to record not only several hundred measurement points but several million measurement points. Thus the measurement accuracy as well as the measurement possibilities significantly increase and at the same time make the measurement easier to handle.

4.2 Gearwheel measurements

For a fast and areal acquisition of the whole geometry of the gearing of precision-forged gearwheels, comprehensive measurement and evaluation strategies were developed on the basis of the fringe projection technique. As a result of the optical and areal measurements an analysis of the whole gearwheel geometry is made possible for the first time. In addition, the measuring time is reduced dramatically, compared to conventional tactile gearwheel measurements.

To reliably control a process chain for the manufacturing of precision forged high performance gearwheels, a production related inspection of the intermediates before the hard finishing is essential. The analysis of the geometric data gives information about the characteristics of the deviations and supplies the actual data for process control. In this way, it is possible to detect wear of the forming die or geometric errors caused by the heat treatment. To eliminate the cause of these systematic deviations, adapted process parameters can be passed on to the corresponding sub-processes.

4.2.1 Data acquisition

Due to the geometric properties of the gearing and the use of preferably small measuring fields [5], the acquisition of the work piece geometry is carried out with respect to the pitch angle. A number of datasets were acquired, according to the number of teeth, where the gearwheel is rotated about the pitch angle between two acquisitions. By this approach many parts of the geometry are recorded redundantly [6]. Hence, areas with high slope, which cause large measuring inaccuracies, can be eliminated from the single measurements, because the neighboring images contain these areas under better optical conditions. Through this technique, it is possible to optimize both the amount of data and the measuring time.

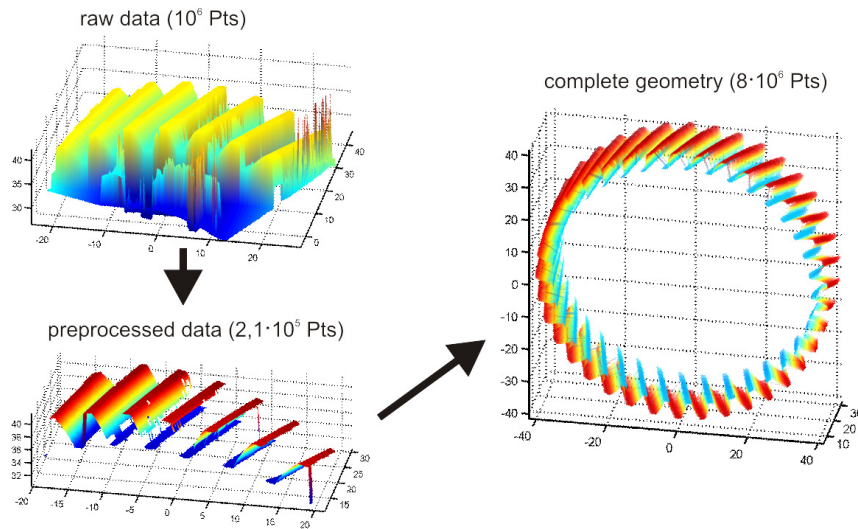


Fig. 12 Recombination of the complete geometry from single measurements

The recombination of the complete geometry is carried out only by means of geometric transformations of the measuring points. Neither complex matching-operations nor registration processes are accomplished. This approach demands a most accurate determination of the rotating axis, which lies outside of the measuring volume. The rotating axis is determined by measurements on a reference cylinder, whose diameter equals the pitch circle diameter of the measured gearwheel [7]. The rotating axis is used as preliminary gearing axis.

Fig. 12 demonstrates the recombination of the complete geometry. After the processing of the raw data the number of measuring points is reduced to approx. $2.1 \cdot 10^5$ per single measurement. The complete geometry of the gearing (approx. $8 \cdot 10^6$ points) is recombined through rotation and translation of the single datasets, with respect to a preliminary work piece coordinate system, which is orientated on the rotating axis.

4.2.2 Evaluation of the gearing deviations

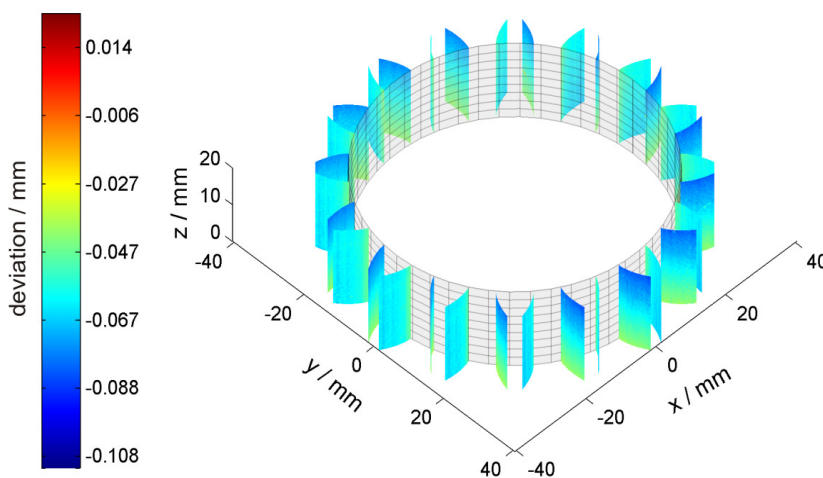


Fig. 13 Illustration of the deviations on the tooth flanks on a geometric model of the tested gearwheel

Of particular interest in the testing of the precision forged gearwheels is a quick visual assessment of the functional surfaces. First, the functional surfaces are extracted from the measuring datasets and fitted on a reference involute. Then, the deviations of the measuring points are calculated orthogonally to the reference. The color-coded results of the optical measurements can be presented very clearly on a three-dimensional model of the tested gearwheel, which can be freely moved and turned in all dimensions.

This kind of illustration allows for a first qualitative evaluation of the gearing deviations. In addition, it is possible to acquire information about the tooth width and pitch deviations indirectly by evaluation of the absolute deviations.

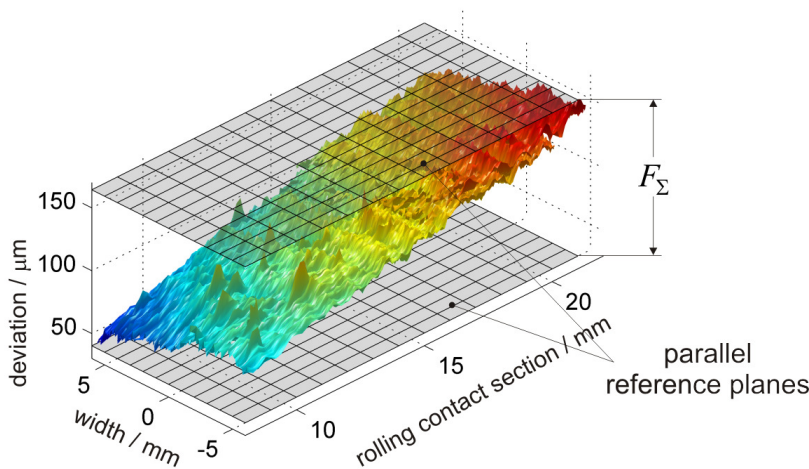


Fig. 14 Definition of the areal parameter F_{Σ} , the total deviation at the gearwheel flank.

A quantitative analysis of the geometric errors, aiming at an objective evaluation, a determination of tolerances and the analysis of manufacturing errors, can be carried out by means of areal parameters, which are partially based on conventional line based gearwheel parameters [7]. As an example, Fig. 14 shows the definition of the areal parameter F_{Σ} , the total deviation at the gearwheel flank. The characterization of the geometric data using areal parameters supplies information about the characteristics of the deviations and supplies the actual data for process control.

5 Summary and forward looking statement

This article introduces the basics and the metrological application of a novel method for optical 3D measurements. The method is based on the phase measuring digital fringe projection technique. As previously shown, it is possible to construct measurement machines that implement the fringe projection measurement technique. These optical 3D coordinate measurement machines, when equipped with the appropriate measurement volume, provide a measurement accuracy comparable to conventional mechanical tactile measurement machines. This novel type of measuring machine offers the specific advantage of measuring several million measurement-points on a tool, component or cutting insert within a very short time period. The large amount of measurement points allows excellent detection of details on the profile of the part. Furthermore it was shown that the use of the software package TopoXenios enables the processing of these measured 3D datasets that contain several million single measurement points. Thus it is possible to extract standardized geometries from the measured 3D dataset based on form, dimension and position. CAD based nominal/actual value comparisons of the measured tool or component can be conducted as well. The given examples of use, measuring and evaluating a cutting insert and a precision forged gearwheel demonstrate just two of the many applications of this innovative measurement technique.

6 Literature

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