

# Tilted Wave Interferometer for the fast, flexible and precise measurement of Aspheres and Freeforms



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## **Abstract**

Functional surfaces with increasing degree of complexity gain more and more in importance for modern industrial products. It is a common insight, that one cannot produce surfaces better than it is possible to measure them. Consequently, the demand for their effective and precise measurement has increased to the same extent as their production capabilities have grown. In cooperation with the company Mahr a research team at the Institute of Applied Optics of the University Stuttgart has developed and implemented an entirely new approach for the precise and effective measurement of important classes of optical functional surfaces: aspheres and freeforms. Both types of surfaces have become essential parts of modern optical systems such as laser focusing heads, sensors, telescopes, glasses, head-mounted displays, cameras, lithography steppers, and pickup heads. For all of them the systematic quality control is of highest importance - especially in the process of their fabrication.

### **1. State of the Art**

It is an accepted fact that our high-tech world could not exist without metrology. Metrology and quality are two sides of the same coin and high quality standards are a must for the majority of manufacturers in all industrial branches. Six Sigma ( $6\sigma$ ) as a measure for quality that strives for near perfection is meanwhile the accepted standard for a wide range of manufacturing processes and products [1]. As an approach that focuses on the nearly total elimination of defects (to achieve Six Sigma, a process must not produce more than 3.4 DPMO - Defects Per Million Opportunities), Six Sigma is strongly connected with the implementation of a measurement-based strategy. The so-called DMAIC process (Define, Measure, Analyze, Improve and Control) is an established methodology to achieve process improvement and failure reduction. However, the environment, where the so-called zero-defect production must be implemented, is becoming increasingly complex. This applies both to the products themselves as well as to the processes of making them.

Optical metrology enables a unique approach for the measurement of surfaces, both technical and optical, over a wide range from macro to nano. Meanwhile a broad spectrum of methods working with coherent or incoherent light is available to cope with the challenges caused by the dramatically increasing quality standards in the fabrication of industrial products. High-precision shape metrology of optical surfaces is a classical task of optical metrology. Optical surfaces are specular surfaces, with roughness values much smaller than a quarter of the used wavelength. Already in the early 20<sup>th</sup> century the application of interferometric principles has pioneered in the production of optical components. Classical interferometers like Twyman-Green, Fizeau, and Sagnac were and are essential tools for the inspection of flats and spherical components. Yet they lose part of their beauty and simplicity when it comes to testing of non-spherical surfaces with low symmetry, such as aspheric and freeform lenses that have become more and more popular in recent years.

Although the application of aspherical surfaces for the correction of spherical aberrations goes back to the 17<sup>th</sup> century, the time of Rene Descartes and Christiaan Huygens, the broad industrial application started only in the middle of the last century. The world's first commercial, mass-produced aspheric lens element was manufactured 1956 by Elgeet for use in the Golden Navitar lens for 16 mm movie cameras [2]. Well known examples are also the Schmitt Plate installed 1960 in the 2 m Alfred-Jensch-Telescope of the observatory in Tautenburg, aspheric pickup heads for optical data storage and reading devices [3], and aspheric lenses for eyewear. Moritz von Rohr (1868–1940) is usually credited with the design of the first aspheric lenses for Zeiss eyeglasses.

Aspheres and even more freeform surfaces feature a bunch of advantages in comparison to conventional spherical elements [4]. An increased flexibility in the design of the functional surface delivers the potential for the elimination of aberrations without making the systems more heavy and bulky. But the prize that has to be paid for this flexibility is not even low. Taking into account that the calculation of a wanted design is no longer a challenge due to the almost unlimited resources in computing power, the fabrication needs high-end surface finishing technology. Shorey et al [5] say quite rightly: *“When contouring a complex surface, the final accuracy becomes much more sensitive to the manufacturing environment, with strong dependence on the positioning accuracy of the machine, the condition of the grinding wheel and vibrations in the system”*. The primary challenge is that the locally varying curvature of the surface requires an appropriate adjustment of the shape of the polishing pad to avoid a local misfit between the optical surface and the tool. Modern shaping and finishing tools like single point diamond turning (SPDT), computer controlled polishing (CCP), ion-beam finishing (IBF) and magnetorheological finishing (MRF) are advanced technologies that cope with these challenges. The assurance of a high process stability and yield requires, however, a continuous monitoring of the surface formation process with respect to form errors, waviness, local defects, footprints of the tool and surface roughness. Consequently, the need for the in-line integration of effective measurement tools is meanwhile a common insight among the manufacturers of precision aspheres and freeforms [6].

Therefore it is not surprising that the first measurement tools were invented as the technology for making aspheres became mature. Traditionally, the quality of the generated surfaces relied largely on the skill of the operator and was assured by a kind of trial-and-error approach. This resulted in expensive manufacturing costs and low production yield. With the rapid development of advanced in-process inspection systems, machine control mechanisms and mechanical design, ultra-precision machining allows for high fidelity in transferring the machine tool motions and the tool profile into a workpiece [7]. In ultra-precision machining, the form accuracy of the machined surface is seriously affected by various sources of error which might be caused by residual stress induced in the surface layers of the workpieces during cutting, wear of the processing tool and tool decentering. These errors can be minimised or even eliminated by applying a bunch of measures for the improvement

of the process stability and precision [8]. However, the prerequisite for this is the continuous observation of the surface quality of the workpiece.

The requirements of the manufacturers of aspheres and freeform optics are oriented on the following **wishlist** [9]:

- The system should allow the measurement of a wide range of surfaces (slope, form, diameter, departure from the best matching sphere).
- The system should be robust against influences from the manufacturing environment, and should be able to be integrated into the workflow.
- The system should allow the continuous monitoring of the surface formation process with the objective of the timely detection of form errors and surface defects without stopping the surface processing for minutes.
- The system should have a verified uncertainty in measurement referring to the Guide for the Expression of Uncertainty in Measurement (GUM) and better than one tenth of the applied wavelength across the whole field.
- The delivered results should be traceable to the international length standard.
- The system should have a lateral resolution of at least a few hundred measurement points across the aperture.
- The system should have a height resolution better than 1nm.

There are different approaches for probing the surface profile: non-contact optical sensing and tactile scanning with a mechanical stylus. In the first case one can distinguish between an areal scan and a pointwise sampling.

One of the *gold-standard* machines for tactile sampling have been for many years the Ultrahigh Accurate **3-D Profilometers from Panasonic** [10]. The UA3P-5 for instance with a measurement volume of 200 x 200 x 45 mm<sup>3</sup> has a specified measurement error of 0.1 µm and a repeatability within 0.05 µm. This high precision within a comparatively large volume and for surface angles up to 60° has to be paid for by a moderate measuring speed of 0.01 to 10 mm/s. The UA3P is the matter of choice for reference measurements and spot checking. But the tactile principle is not suitable for continuous areal monitoring of the surface formation process.

For the noncontact optical topology measurement of aspheres with a diameter up to 420 mm LUPHOS offers a multi-wavelength based interferometric point sensor **LuphoScan** [11]. For the scan of an asphere with a diameter of 130 mm the device needs approximately 5 minutes with a point density of 50 points/mm<sup>2</sup>. A feature which limits the application range is given by the fact that the device can be applied only for the inspection of rotational symmetric specimens. Freeform optics is not a subject of this solution.

Other approaches measure the local gradient of the surface instead of the topography itself. The final shape is found by integration. An example is the deflectometric measurement principle for specular surfaces [12]. It has been commercialized both as point scanning method (e.g. **Trioptics** [13]) or camera based as a full field method (e.g. **3D-Shape** [14]) and has found its application e.g. in eye-

glass testing but also as a method for testing focusing mirrors, e. g. in astronomy [15]. The principle allows for the detection of high-frequency surface defects with a size of few nanometers. But due to the integration step involved the absolute curvature and low-frequency surface errors tend to be detected with a lower accuracy, which is a disadvantage compared to interferometry. A direct traceability as in case of interferometry, where the measured phases can be traced back directly to the wavelength definition of the meter, is not possible.

Optical interferometry is a well-established and very sensitive method for the form measurement of aspheres [16]. The most serious challenge for all optical metrology approaches is vignetting, i.e. if the local departure of the surface under test is too strong, the test wave is reflected off the surface such that the light does not reach the sensor anymore and the surface cannot be measured in that area. Therefore so-called compensation optics comes to play with the objective to compensate these departures. State of the art is the use of **Computer Generated Holograms (CGH)** [17-19], where the perfect shape of the asphere under test is encoded in the CGH. The full field measurement then reveals the deviations from this perfect shape. The drawback of such holograms is, that for every design shape to be tested, a matching CGH has to be fabricated, which is costly and time consuming. Other technologies, like sub-Nyquist interferometry [20], multiple-wavelength-interferometry [21], stitching or scanning interferometry, are more flexible [22, 23]. Multiple-wavelength-interferometry has the advantage of absolute testing but as sub-Nyquist interferometry cannot solve the problem of vignetting. Stitching interferometry, e.g. with the **ASI (Q)** measurement station from **QED** [24], is able to measure a wider range of aspheres with up to 1000 waves of departure from the best matching sphere without relying on dedicated, expensive null-optics. However, the surface has to be measured patch by patch in many time-sequential steps. To adjust the sub-aperture interferometer to every local patch, a high-precision and flexible multiaxial kinematics has to be implemented. Even though the number of patches can be reduced using a so-called Variable Optical Null (VON) Technology that generates a wavefront that closely matches the local aspheric shape of each subaperture being measured, the measurement takes a couple of minutes up to hours dependent on the number of sub-apertures. In the scanning interferometer **Zygo Verfire Asphere** [25] the asphere or the interferometer head have to be shifted along the optical axis with a motorized stage and the results of the ring zones have to be combined. The principle works for rotational symmetric surfaces but fails for general freeforms. For both the QED and Zygo principle, a single measurement takes several minutes.

## 2. The Tilted Wave Interferometer

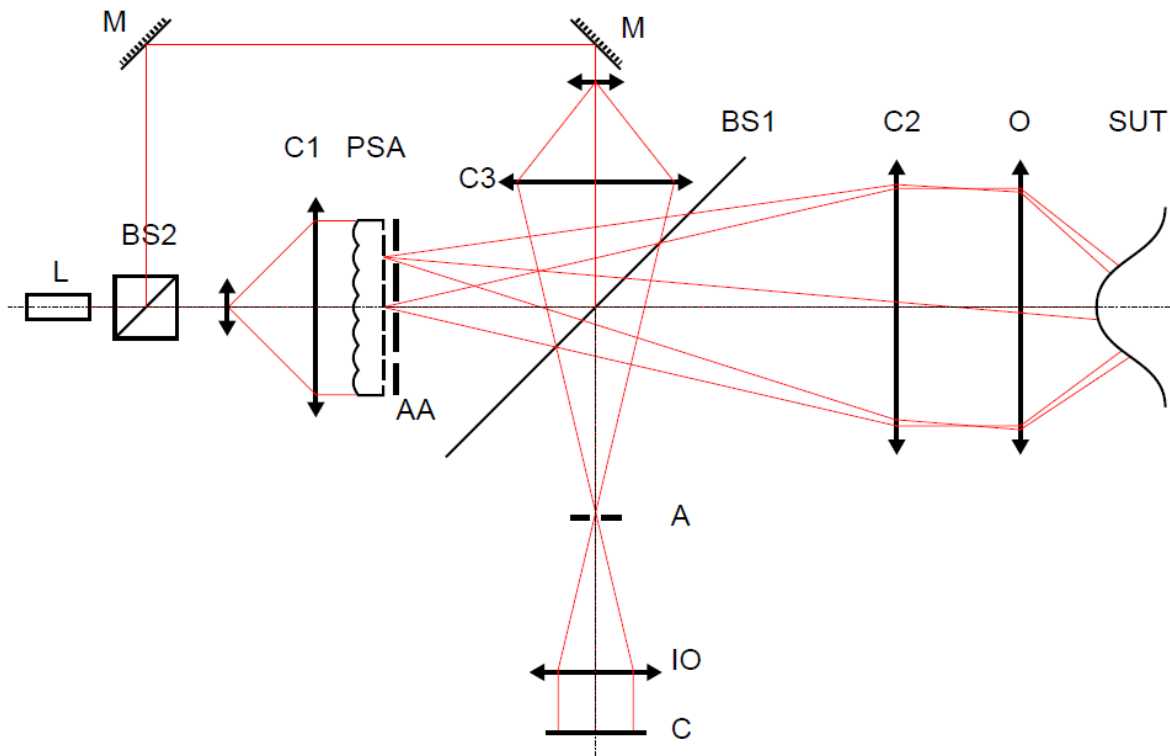
The **Tilted Wave Interferometer** (TWI) [26,27], which was invented by a research team of the Institute of Applied Optics (ITO) at the University of Stuttgart and developed to a commercial tool by the company Mahr, is a flexible tool for the high-precision and fast measurement of aspheres and freeforms. It combines the high accuracy and traceability of the interferometric principle with a high dynamic range of up to  $10^\circ$  gradient deviation from the spherical form, without the need for compensation optics and moving parts. Furthermore it has - like all full field interferometric methods - a high lateral resolution. An outstanding feature is its short measurement time, which is achieved by a highly parallelized data acquisition. In principle it is a single shot technique that allows the robust measurement of the entire surface in few seconds with a height resolution better than 1 nm and a lateral resolution of several microns. The unique combination of these features makes the TWI a perfect candidate for the integration into the manufacturing workflow for aspheres and free-form production.

These features are mainly achieved by the implementation of an innovative and **patented illumination design** [27] in combination with a new calibration concept. The solution of the tilted wave interferometer is both simple and effective. It extends the single spherical wave front of a standard interferometer to an array of mutually tilted wavefronts. All of them simultaneously impinge onto the surface under test (SUT). Thus for each area on the SUT there is a fitting wave front that compensates the local deviation from the best fitting sphere such that the laser light reaches the camera and produces interference fringes that contain the desired surface shape information. Since all wave fronts are there simultaneously, the SUT can be measured very quickly. In principle the measurement time can be reduced to a single shot measurement. But in practice, it has proved advantageous to have four subsequent measurements with individual illumination settings to avoid overlapping of adjacent interferogram patches. Anyhow, the measurement time lies within a few seconds, while the allowable aspheric or freeform departures from best fit sphere can be strong and of the order of several hundred micrometers.

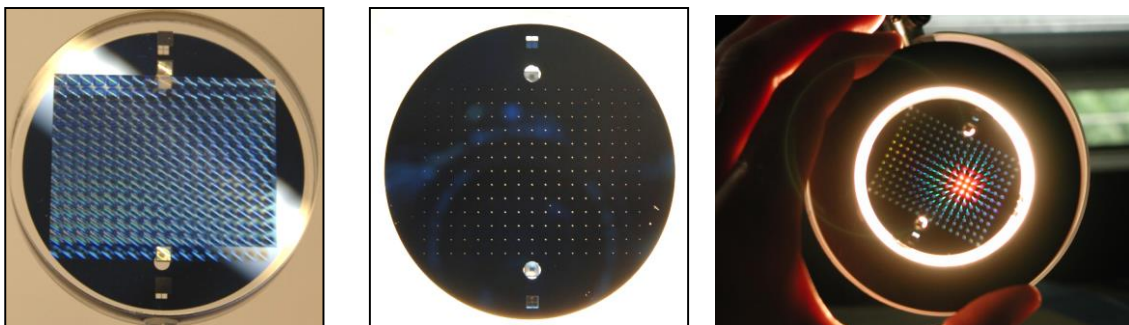
Any setup that needs to measure surfaces with an accuracy better than a fraction of the wavelength relies on careful calibration, since at this nanometer accuracy level systematic errors from an imperfect setup are inevitable. A unique feature of the new TWI method is the powerful **new and patented calibration concept** [28, 29] which can be generalized to other types of interferometric setups and which guarantees a reliable and verified precision in the range of  $\lambda/10$  across the entire SUT. It takes the common standard calibration from a two dimensional areal calibration to a volume calibration. This allows to place the SUT at any suitable position in front of the interferometer, which greatly enhances the flexibility of the instrument.

### 3. The technical solution

Fig. 1a) shows, how the tilted wave fronts are realized with the help of a matrix of point sources. The matrix of point sources consists of an especially designed micro lens array that is followed by a pinhole array. Both parts together serve as point source array PSA for the test wavefronts (Fig. 1b). The spherical wavefront from each point source is, after passing the beam splitter BS1, collimated by the lens C2 resulting in a set of plane wavefronts with different well defined amounts of tilt. The **tilted wavefronts** are transformed to spherical wavefronts by the objective lens O to compensate the basic spherical form of the surface under test.



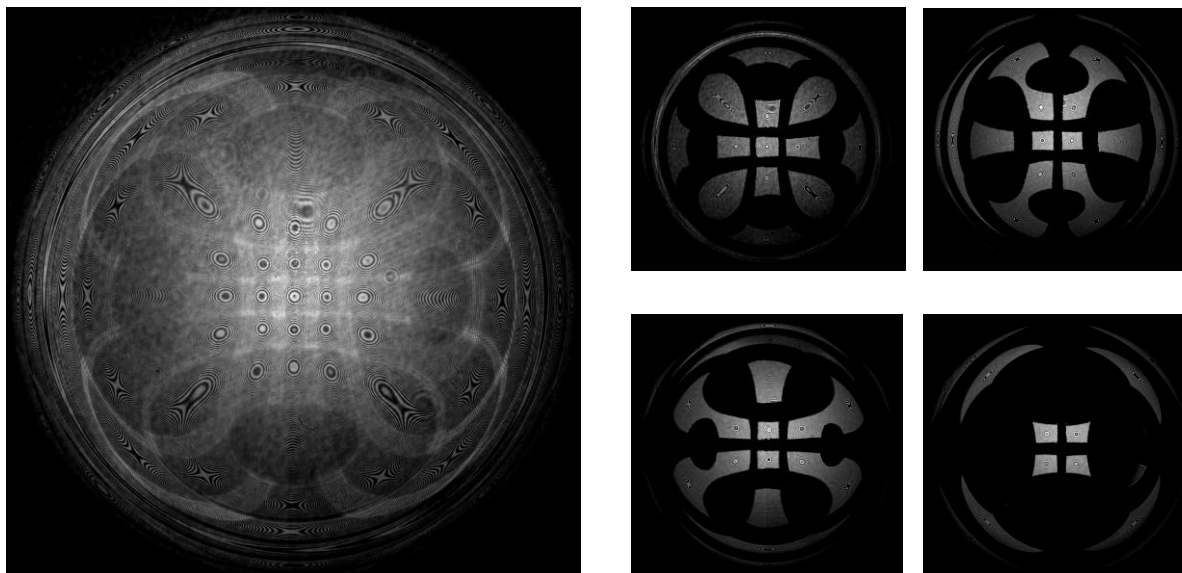
- a) Schematic setup of the interferometer with the central source and one exemplary off-axis source indicated. L: Laser source; BS1, BS2: Beam splitter; C1, C2, C3, Lens; PSA: Point source array; AA: Aperture array; M: Mirror; O: Objective; SUT: Surfaces under test; A: Aperture; IO: Imaging optics; C: Camera;



- b) Point Source Array PSA consisting of a micro lens array followed by a pinhole array

**Fig. 1:** Tilted Wave Interferometer TWI. a) Schematic Setup, b) Point Source Array PSA

After reflection at the surface under test the wavefronts propagate back to the beam splitter BS1, where they are reflected to the camera arm of the interferometer. Here the wavefronts coming from different parts of the surface under test SUT interfere with the reference wave which is propagating along the reference arm. In the Fourier plane an aperture stop A blocks all light that would generate fringes with a density that violates the Nyquist criterion. The generated composed interferogram (see Fig 2) shows simultaneously all sub-apertures of the SUT with resolvable fringe density. Consequently, the complete SUT can be evaluated by a single coherent illumination without moving any component of the interferometer. However, to avoid crosstalk between adjacent patches, only every second point source is activated simultaneously by a switchable aperture array. Therefore, a 4-step procedure is preferred taking a few seconds longer. In all patches the resolvable result of the interference between the reference wave and the particular tilted wave coming from the corresponding patch of the SUT can be evaluated.



a) Composed interferogram

b) 4 interferograms after steplike activation of every second point source

**Fig. 2:** Composed interferogram showing all subapertures of the complete surface under test (SUT) with resolvable fringes

All tilted wave fronts propagate simultaneously through the interferometer along various ways, allowing an instantaneous measurement of the entire SUT. However, this benefit generates a serious challenge. The interferometer is no longer a common-path arrangement. In a null-test configuration, a ray impinges perpendicularly on the surface and takes (after being reflected by the surface) the same path back through the interferometer. Therefore it is sufficient in conventional setups to calibrate the OPD that is introduced by the interferometer for each pixel coordinate on the camera. The calibration can be expressed as a 2-dimensional phase map  $f = f(x,y)$  with  $x$  and  $y$  being the coordinates of the pixel and  $f$  being some polynomial function or a look-up table containing the OPD correction value for each pixel. The intrinsic non-null setup requires a much more **sophisticated calibration**



where spatial and field dependencies are not decoupled anymore and the relationship has to be replaced by a more involved relationship. The ray impinges onto the surface under an angle that may differ from the perpendicular case and therefore the ray may take an arbitrary path through the interferometer, introducing retrace errors to the measurement. As a result, a 2-dimensional calibration is not sufficient, since the introduced OPD also depends on the field angle, i.e. how the light passes through the setup. This can be described as a 4-dimensional dependency  $f = f(x;y;m;n)$ , where two dimensions (x and y) cover the spatial dependency of the phase, as in the null-test example and the other two dimensions (m and n) cover the field dependency. With such a 4-dimensional description any possible ray through the system can be described, as long as we chose the position for the reference plane in a region without any caustic. The complete calibration procedure is described in [28] and filed as a patent [29]. Together with the unique illumination concept, the calibrated TWI embodies a completely new solution for the fast, flexible and precise measurement of aspheres and freeforms.

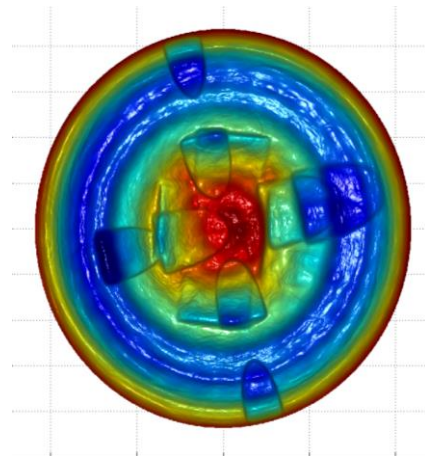
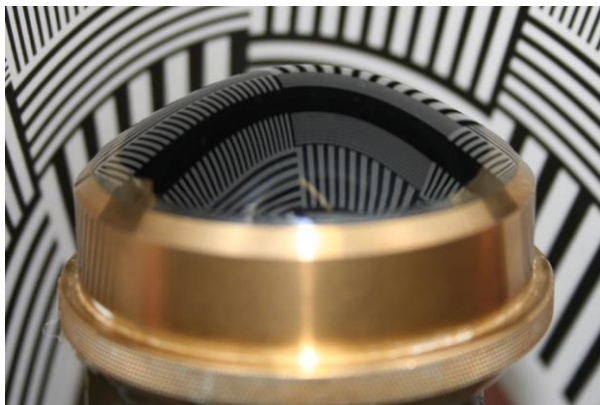
#### 4. Advantages compared to the state of the art

As reported in § 2, the customers of measurement systems for in-process monitoring of the surface quality of manufactured aspheres and freeforms have a clear idea about the required features of the device. The objective of the invention, development and commercialization of the Tilted Wave Interferometer TWI (see Fig. 3) was the compliance with these requirements to the greatest possible extent. So far none of the systems and procedures listed in § 2 could simultaneously demonstrate a high measurement speed, great flexibility in the variety of measurable shapes including freeforms, robustness, and high measurement point resolution with the required accuracy.

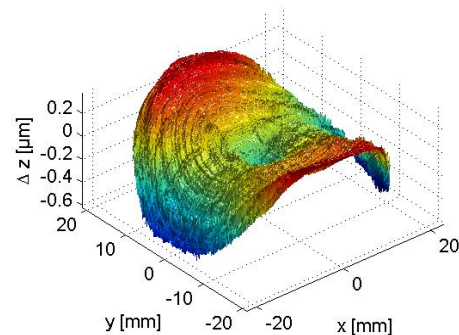


**Fig. 3:** The MarOpto TWI 60 as presented at the Optatec 2016 in Frankfurt, Germany

In comparison to the state of the art (see Chapter 2.), the interferometer MarOpto TWI 60 [30] combines the high accuracy and traceability of the interferometric principle with a high dynamic range of up to  $10^\circ$  max. gradient and appr. 1,5 mm max aspheric departure from the best fitting spherical form without the need for compensation optics and complex kinematics. It is able to measure both aspheres and freeforms. Furthermore it has - like all full field interferometric methods - a high lateral resolution across the full aperture (several hundred measurement points in diameter). An outstanding feature is its short acquisition time (appr. 30s), which is achieved by the highly parallelized data acquisition and which allows the integration into the workflow without unwanted delay in the processing chain. In principle it is a single shot technique that allows the robust measurement of the entire surface in few seconds with a height resolution better than 1 nm and a lateral resolution of several ten microns..The unique combination of these features makes the TWI a perfect candidate for the integration into the manufacturing workflow for aspheres and free-form production.



- a) Aspheric surface: Best fit radius = 34,32mm, Asphericity =  $600\mu\text{m}$ , Slope deviation =  $8^\circ$       b) Surface deviation map showing the footprints of the processing tool



- c) Diamond turned free-form surface: Base radius:  $R = 52\text{ mm}$ , Astigmatism:  $800\mu\text{m}$  (PV)      d) Surface deviation map showing typical diamond turning artifacts

**Fig. 4:** Exemplary measurement of an asphere and a free-form

## 5. Benefits for the practical use and Conclusion

For the user, the crucial advantage of the new principle in comparison to existing measurement systems is the high flexibility with respect to the shape of the SUT, the high lateral and depth resolution, the low measurement uncertainty combined with the short measurement time. The MarOpto TWI 60 has the real potential for an in-process measurement system. Freeform lenses for augmented reality systems, for instance, are on the way to become a worldwide mass product. Here a completely new market segment with a rapid growth is on the way. It is a common insight among optics manufacturers and their processing technology that this needs an adequate quality assurance based on a continuous monitoring of the surface formation of any individual lens for reasonable costs. The TWI is ready to meet this challenge.

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