Non-contact inspection of complex optical components

Innovative optics with complex geometries broaden the scope for innovative manufacturing processes – and present new challenges for metrology. The combination of a highly accurate fiber-optic sensor and a precision-guided kinematic unit makes it possible to perform a fast 100 % inspection at the production line.

Frank Depiereux, fionec GmbH
Kurt Rämer, Fraunhofer Institute for Production Technology IPT

The introduction of optical technologies into manufacturing has opened up new avenues for developing new products and processes. Until now, it has only been possible to partly realize the potential of technological advances, such as those in the field of laser light generation, due to the limited performance of current beam guidance systems. Novel quartz and diamond optics with complex geometries, such as aspheric lenses, free-form surfaces and array structures, are set to significantly expand the range of possible applications in future.

A new manufacturing process is being developed as part of a research project for the precision molding of fused silica (**figure 1**). One of the challenges this manufacturing process poses concerns the heavy tool wear resulting from the high temperatures and pressures involved in the molding process. Micro-cracks on the molding tools and adhesions impair surfaces and, as a consequence, the optical properties of the lenses. Because of this, continuous metrological quality control is necessary.

The parameters that affect the function and performance of the optical components are surface topography and roughness. Tolerable deviations lie in the sub-micron range. Besides being highly accurate, a suitable measuring system must also ensure that the inspection process is fast, near-line and above all, non-contact. Tactile measuring devices are thus of only limited interest for inspecting optics.

Near-line solution

In contrast to styluses, optical sensors work without coming into physical contact with the specimen and thus non-destructively. The high measurement frequencies mean that very short inspection times and high measurement point densities can be realized. They can be relatively easily integrated into existing production lines to perform in-line measurements too.

Figure 1: Molding tool with lens

Established systems for inspecting optics tend to use laser or white-light interferometers due to the required levels of accuracy. The potential applications for optical measuring systems in inspecting optics are limited less by the measuring method itself than by the shape and size of the measuring device used, however. When it comes to very small, densely packed arrays, concave-shaped specimens or complex free-form surfaces in particular, a standard sensor head is likely to hit the flanks of adjacent components. This makes space-saving, near-line inspection processes difficult to realize.

Non-contact micro-metrology

It is for this reason that fionec GmbH and the Fraunhofer Institute for Production Technology IPT are developing a fiber-optic precision measuring system with highly accurate sensors and miniaturized probes. The specially made probe has a diameter of 1.4 millimeters and can be used even for small, concave components (**figure 2**). Thanks to its diminutive size, the microprobe can be easily integrated into a variety of measurement and inspection instruments with almost no addition of weight, or built directly into ultra-precision optical component manufacturing machines.

The measuring probes are based completely on fiber-optic technology. The use

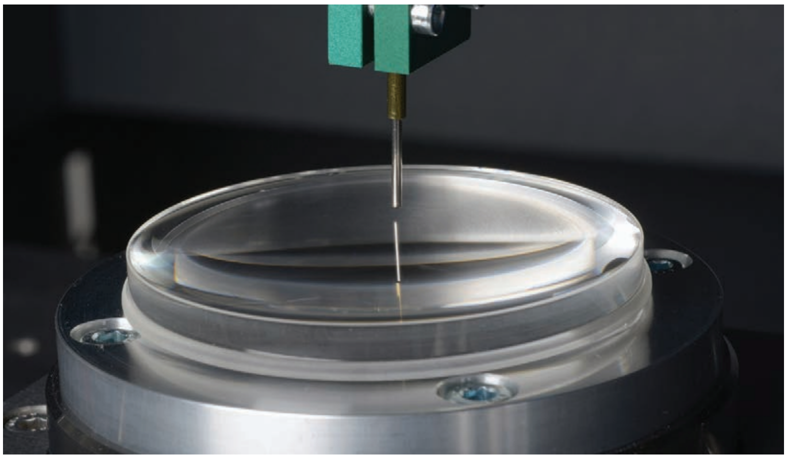

Figure 2: Fiber-optic probe during the measuring procedure (test object: aspheric lens)

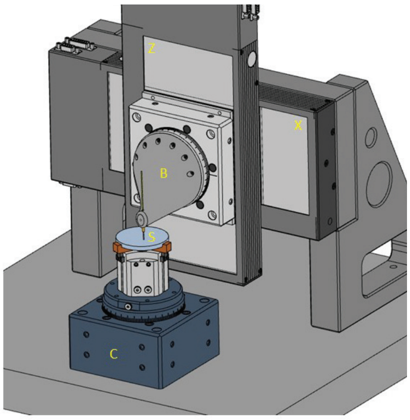

Figure 3: Schematic diagram of the precision kinematic system

of optical fibers makes it possible to custom-manufacture the probes and miniaturize them down to an external diameter of just 80 µm. There is almost no restriction to the length of the connection between probe and analysis unit. This makes the measuring system extremely flexible, robust and suitable for deployment in an industrial environment.

The fiber-optic measuring system operates based on the principle of low-coherence interferometry [1] and as such offers two decisive advantages over laser interferometry: Firstly, it makes measurements of optically rough surfaces possible, and secondly, the measurement is absolute. This means that the measured value is not lost even in the event a measuring process is interrupted – e.g. due to shading of the measuring beam or surface defects.

This interferometric technique involves the light from a low-coherence, fiber-coupled source being guided into an optical coupler and transmitted from there to the actual measuring probe. The waves are split into reference and measuring signal at the probe. On their return, the waves interfere with each other in the opto-electronic analysis unit. The interference pattern created can then be converted into a distance value.

The interference principle ensures a high degree of measurement data accuracy, which is required by virtue of the surface finish and low manufacturing tolerances of the optical components being tested. The comparatively large numerical aperture of the probes of 0.20 means they can measure flank angles of up to 10° without degrading signal quality. Larger flank angles can be measured by adjusting the position of the probe.

The high measuring frequency of up to 8 kHz and a measurement uncertainty of under 10 nm makes the technique ideally suited for quick and accurate surface measurements. Even free-form surfaces without rotational symmetry can be measured using interferometric sensors.

Precision kinematics

In order that the sensor is able to measure as wide a range of surface forms as possible, the position and angle of the probe must be precisely adjusted for the specific surface. Deviations resulting from guiding and positioning the sensor by the kinematic system are generally incorporated directly into the measurement result as measurement uncertainty. For this reason, special attention during development was paid not only to the sensor technology, but to the precision-guided, multi-axis kinematic unit too (**figure 3**).

The precision kinematic system is designed to perform full-surface scans using freely programmable scanning paths. Two linear axes (X, Z) and a rotational axis (B) position the measuring probe (S) with high precision according to the defined target contour. The probe is positioned orthogonal to the optical surface.

The component being inspected is fixed to another high-precision, air-suspended rotational axis (C) so that it can rotate beneath the optical probe during the measuring process. This setup enables the system to measure both spherical and aspheric lenses, and – thanks to the compact size of the measuring probe – convex and concave lenses too. The probe is guided on the basis of the target shape, which can be stored in the system based on CAD design data, for example.

The distances between measuring points can be individually set for specific regions of the surface dependent on the particular measuring task at hand. Very high point densities are required for determining roughness values. Significantly fewer points, and thus very short inspection times, are required to measure the shape. If need be, topographical deviations and roughness parameters can be measured during a single measuring procedure (**figure 4**).

Standardized analysis

A special software application is being written to analyze the optically measured values. This both controls the movement

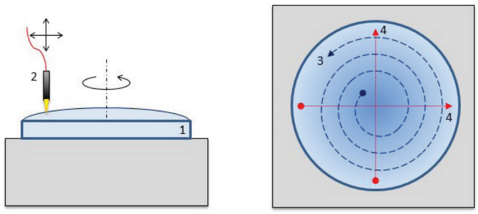

Figure 4: Left: The rotation of the optical components (1) and the linear movements of the measuring probe (2) enable the integrated precision measuring system to conduct full-surface scans with customizable scanning resolutions (1). Right: The sensor measures shape (3: spiral path) and roughness (4: linear scans) in a combined measuring process.

of the sensor and combines the data from kinematic system and sensor to create a three-dimensional point cloud.

The recorded data makes it possible to determine the deviation in shape and the relevant linear (R) or surface (S) roughness parameters. The calculation is based on the relevant standards for evaluating roughness. Deviations in shape are revealed using a target/actual comparison and displayed by the software as false colors or deviation vectors. In future, it will be possible to input the target contour into the system as a CAD file and by entering appropriate grid points or the aspheric coefficients in accordance with ISO 10110 (**figure 5**).

Measurement results

During the initial phase of the DPP (Digital Photonic Production) research project, the pre-assembled fiber-optic sensors were first used for preliminary testing in a high-precision coordinate measuring machine (CMM). This measuring setup was used to record high-resolution scans of a molded convex aspheric lens. **Table 1** summarizes the most important parameters of the test.

In order to only need to move one axis during the measurement procedure and thus minimize sources of errors due to the kinematic system used, it was decided to use parallel-offset linear scanning as the measurement strategy. A total of three fields (A, B, C) were scanned with the sensor using different point densities. **Figure 6** depicts the 3D point cloud for field A. It should be noted that the z-axis was scaled up by a factor of around 15 in order to better represent the spherical shape of the aspheric lens. >

Images: Fraunhofer IPT

It can be clearly seen in **figure** 7 how the measuring point density increases as the size of the measurement field decreases. Conversely, this means that the sensor can measure larger measurement fields, such as those used for determining topographical deviations, more quickly. If high resolution is needed for a roughness evaluation, the point density can be specifically adjusted for a small measurement field. Even at these high resolutions, the optical sensor operates up to ten times faster than comparable tactile methods.

Using the data from measurement field A, the radius was determined by means of a spherical best fit in CloudCompare [3]. The design data for the aspheric lens specifies a target radius of 205.165 mm, the comparison tactile measurement returns a value of 205.713 mm and the optical measurement 205.027 mm.

It is expected that refinement of the DPP precision kinematic system will minimize external sources of error thus increasing the reliability of the measurement data. The new measuring system will return both topographical deviation and roughness parameters in much shorter times than has thus far been possible with traditional measuring devices. Moreover, an integrated total solution can be offered at far more attractive terms than a commercially available combination of two devices for examining surface form and roughness.

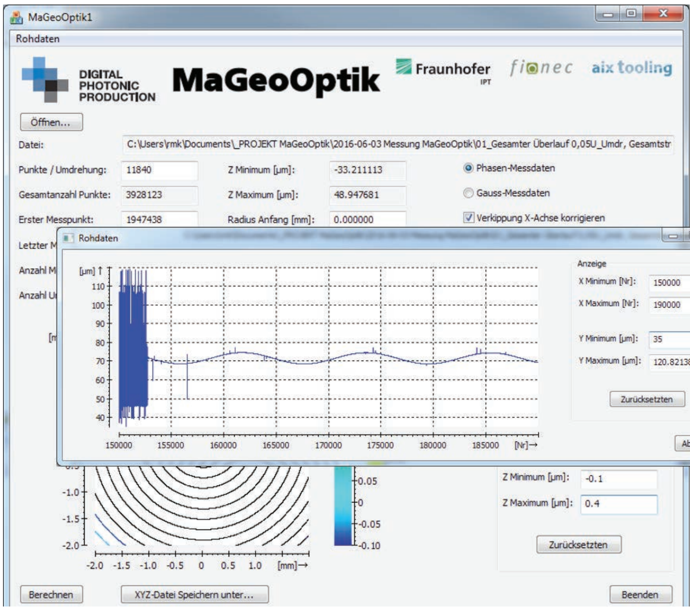

Figure 5: Prototype analysis software

Conclusion

The integrated fiber-optic measuring system offers a reliable, and above all, non-contact alternative to tactile methods for measuring complex optics. The new technology makes it possible for the first time to perform areal scans of free-form optical surfaces using custom-programmable scanning paths, and not only analyze topographical deviations, but also roughness parameters in a precise and non-destructive way.

Because the fiber-optic sensors work almost irrespective of the surface, the system is able to perform measurements on components made from other materials too. The extremely compact design of the probe head with a diameter of ≥ 80 µm represents a major advantage for all measurement processes. In combination with a kinematic unit, the sensor can even be used for microscopic holes and other difficult-to-access installation spaces.

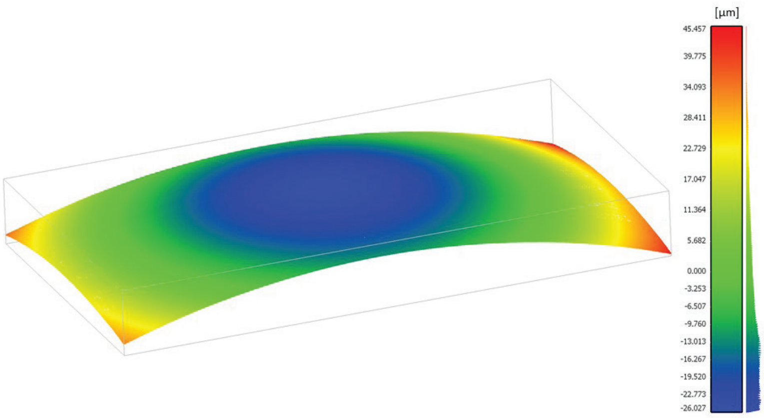

Figure 6: 3D representation of the measurement result (test object: aspheric lens). It shows the distance to the z plane in microns.

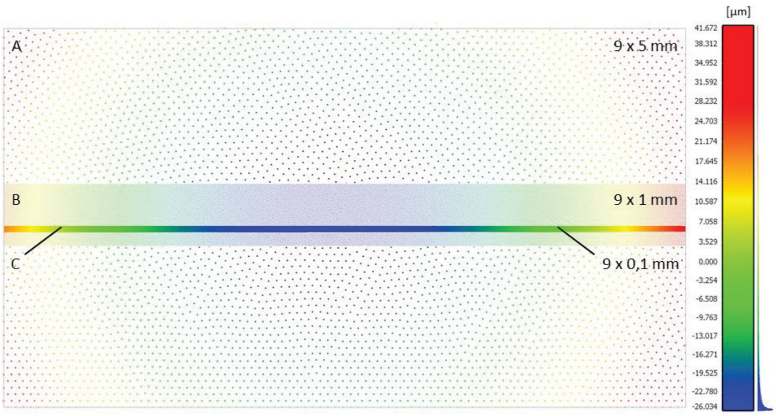

Figure 7: Different measurement fields of varying sizes and point densities (test object: aspheric lens). It shows the distance to the z plane in microns.

[1] F. Depiereux,P. Lehmann, T. Pfeifer, R. Schmitt, Fiber-optical sensor with miniaturized probe head and nanometer accuracy based on spatially modulated low-coherence interferogram analysis, Applied optics 46 (17), 2007, p. 3425–3431

[2] F. Ströer, J. Seewig, F. Depiereux, Vergleichbare Ergebnisse. Rauheitsmessung taktil oder optisch?, Qualität und Zuverlässigkeit, QZ 59 (05), 2014, p. 70–72

[3] CloudCompare: 3D point cloud and mesh processing software, *www.cloudcompare.org*

Measuring system implementation

As part of the collaborative project MaGeoOptik of the Digital Photonic Production (DPP) Research Campus, the companies fionec and Aixtooling are working together with the Fraunhofer IPT on increasing the performance of beam guidance systems. To this end, optical systems are being fabricated and evaluated using new materials and geometries (Aixtooling/IPT). In order to characterize the new optics with high levels of precision, a fiber-optic measuring device (fionec) combined with a precision kinematic system (IPT) is used to measure the shape and roughness of the lenses.

The collaborative project is scheduled to run until September 30, 2019 and is being supported by the German Federal Ministry for Education and Research (BMBF) to the tune of 1.7 million euros.

Measuring system	Fiber-optic, low-coherence interferometer with miniaturized measuring probe (d= 1.4 mm) for determining form and roughness parameters [2]
Kinematic system	Coordinate measuring machine with 3D length measurement accuracy in accordance with ISO 10360: (0.75 + L/500) µm
Test specimen	Convex aspheric lens
Measuring strategy	Parallel-offset linear scans
Size of the measuring fields	A= 9 x 5 mm² / B= 9 x 1 mm² / C= 9 x 0.1 mm²
Distance between measuring points	A= 0.1 mm/B= 0.01 mm/C= 0.001 mm
Total number of measuring points	A= 4,360 / B= 68,800 / C= 704,000

Table 1: Measurement setup parameters

Images: Fraunhofer IPT, fionec

Contact

Dr. Frank Depiereux
CEO
fionec GmbH
Ritterstraße 12 a
52072 Aachen
Germany
Tel. +49 (0)241 8949 8840
Fax +49 (0) 241 8949 8888
info@fionec.de
www.fionec.de

Kurt Rämer
Fraunhofer Institute for Production Technology IPT
Steinbachstraße 17
52074 Aachen
Germany
Tel. +49 (0)241 8904 417
Fax: +49 (0) 241 8904 6417
kurt.raemer@ipt.fraunhofer.de
www.ipt.fraunhofer.de/en