VERSATILE APPLICATIONS OF LASER FOCUS PROBES IN PRECISION MEASUREMENT TECHNOLOGY

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Abstract:

Big challenges in precision measurement technology nowadays lead to the creation and improvement of a big variety of optical and tactile probes. This development concerns a nanosensor system on the basis of a non-contact laser focus probe (base sensor) which presents high resolution and low uncertainty. Optical and mechanical probing methods are combined on the basis of a laser focus sensor, thus allowing the combination of various interactions between sensor and specimen. For these purposes, the deflection of the probing sensor (cantilever or stylus) is measured directly without contact using the laser beam of the focus sensor. The significant advantage of the developed nanosensor system results from its modularity and versatility. Scanning laser focus sensors are a viable alternative enabling the measurement of non-periodic features. Severe limitations are imposed by the diffraction limit determining the edge location accuracy. A rigorous model for the simulation of the diffraction of three-dimensional focussed optical beams from line space patterns has been developed and applied to improve the edge detection accuracy of a laser focus sensor. The validation of this method is realised by means of an AFM part of the nanosensor system.

Moreover, the possibility of using the laser focus senor not only for precision measurements, but also for the direct generation of precision nanostructures by means of lithography can be shown. Here, compared with classical lithography the goal is to ensure the capability of processing freeform structures on tilted surfaces.

Keywords: nanosensor, lithography, laser focus probe

1. INTRODUCTION

The motivation for the present scientific work was to develop a nanosensor system based on a non-contact optical probing sensor (base sensor) for high-precision profile height measurements which is taloured, above all, to the measurement applications in the NPM-machine. Thus, this base sensor must satisfy very high requirements concerning height resolution, measurement uncertainty and stability.

On the basis of some fundamental studies, we were able to set up a probing sensor of this kind in the form of a focus sensor whose parameters best fulfil the requirements and tasks set. This includes, for example, a vertical resolution of < 1 nm, a focus spot of about 0.6 µm, a working distance of up to 10 mm, and scanning speeds of up to 8 mm/s realised at nanometer reproducibility.

The use of a hologram-laser-unit as central component part of the focus sensor, in connection with specially developed and adapted electrical and mechanical solutions has enabled the realisation of a very compact and comparatively simple sensor design. Thus, it was possible to achieve a high stability and good reproducibility of the measuring system. Here, the use of the null detector measuring method was very important. As it was shown by practical investigations, this method has turned out to be the optimum method for high-dynamic, high-resolution applications in the big measuring volume of the NPM-machine of 25 x 25 x 5 mm³.

The metrological properties of the focus sensor set up were comprehensively studied. For example, reproducibility measurements on calibrated step height standards were carried out. They showed good conformity with the calibration values of < 1.3 nm obtained by the PTB. A temperature stability of the sensor of about 70 nm/K was proved, which corresponds to a change of about 3 nm at a real temperature stability in the cover of the NPM-machine of ± 0.02 K.

A number of very practical measurement examples demonstrate some important properties of the focus sensor by pointing out not only the good advantages, but also their limits of application [1].

Furthermore, a compact camera microscope was developed and combined with the focus sensor. Thus, it becomes possible to follow the probing and measuring process, which allows the user to quickly identify any interesting measurement fields in large regions.

In order to create the desired nanosensor system and to improve the functionality of the optical nanosensor, two tactile probing sensors were finally set up on the basis of the focus sensor, and examined: a focus-stylus-sensor and a focus-AFM-sensor. Thus, a number of efficient alternatives for various limitations of the focus sensor (lateral resolution, diffraction phenomena on edges) could be shown.

Here, the modular design of the sensors and of the camera microscope permits a fast and convenient alternation from one probing method to another one. This was realised in a platform on the basis of a microscope revolver [2].

The excellent metrological properties of the two tactile sensors have been illustrated by numerous practical measurement examples, too.

2. STRUCTURE OF THE NANOSENSOR SYSTEM

2.1 Structure of the base sensor

The hologram-laser-unit as major component part of the focus sensor is equipped with all necessary optical and opto-electronic components which are completely aligned to each other. Otherwise, those component parts would have to be adjusted manually, which is very complicated, in order to be able to set up a measuring sensor according to the focus detection principle. For making the focus sensor complete, two more optical components must still be added, the collimator lens and the objective lens. These two lenses must be attached axially to the hologram of the unit. They are selected in accordance with the specifications indicated for the DVD-playback: as collimator a lens with NA = 0.11 (f = 22 mm) is recommended, and as objective a lens with NA = 0.60 (f = 3.3 mm) is appropriate.

As a result of the investigations, a principle structure of the focus sensor was chosen. Between the collimator lens and the objective lens, an additional beam splitter was mounted which allows the combination of the focus sensor with a microscope. This beam splitter must be polarising in order to transfer the maximum output of the laser diode on to the test object and to minimize at the same time the disturbances caused by the reflected laser beam on the camera chip of the microscope. The application of the hologram-laser-unit enables the setting up of an extremely compact focus sensor which can be adjusted in a most convenient way.

The overall set-up of the focus sensor including the camera microscope mentioned above is shown in Fig.1. The housing of the microscope consists of three main parts: tube, lighting module, and intermediate cover. The light for illuminating the microscope is fed from a cold light source with adjustable halogen lamp output via fibre-optical cables.

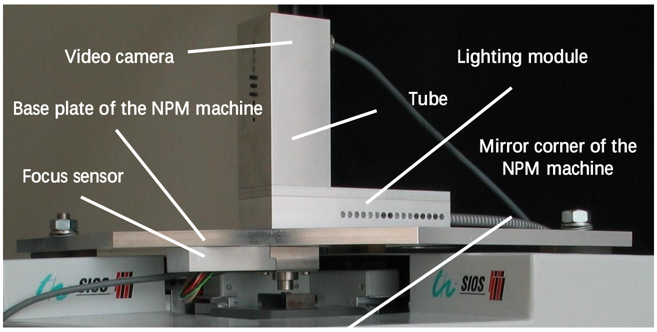

Fig. 1: Focus sensor with camera microscope integrated into the NPM-machine

The design of the microscope is such that all component parts (except from the beam splitter) can be adjusted individually. Furthermore, the lighting components can be adapted to different camera types (chip sizes), objective lenses, and tube lenses. Thus, the microscope magnification can also be varied by inserting various tube lenses. The aperture diaphragm and the field diaphragm have been selected as mechanical iris diaphragms.

2.2 Tactile probes on the basis of the focus sensor

The stylus measuring principle is generally known. In practice, mainly capacitive and inductive sensors are used for measuring the profile-proportional movement of the stylus. In our case, this movement is optically detected by means of the focus sensor (Fig. 2). For this, the laser beam of the focus sensor is focussed on the back of the stylus, and the focus error signal is then utilized exactly as in the case of a purely optical probing for the profile determination of the specimen. Here, the function principle remains unchanged: position control to the null point of the focus sensor characteristic line. In order to eliminate the influence of the local unevenness or also roughness of the back of the stylus, a thin reflecting silicon waver (about 2 mm²) has been mounted on the back.

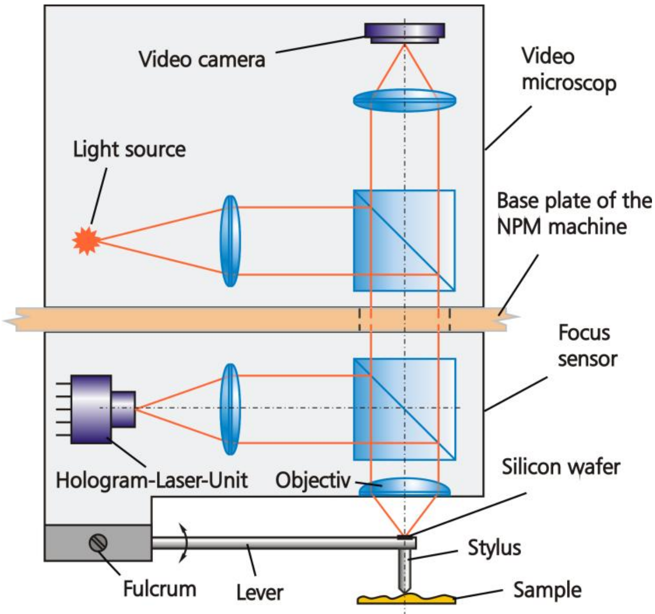

Fig. 2: Principle of a focus-stylus-sensor on the basis of the focus sensor

An essential advantage of the null indicator measurement over the deflection method applied by conventional stylus instruments is that the measurements can be made with constant measuring force. Furthermore, the arc error is eliminated through direct aligned probing, with the position of the stylus being unchanged.

Another advantage over conventional stylus instruments is that the vertical movement of the measuring tip is measured aligned to the symmetry axis of the focus sensor. Thus, errors of first order are avoided, and the Abbe-principle of the NPM-machine is maintained.

The function principle of the focus-AFM-sensor is also based on a combination with the focus sensor. Exactly as in the case of the focus-stylus-sensor described above, the laser beam of the focus sensor is now focussed on the back of the cantilever while utilizing the focus error signal for determining the deflection of the cantilever following a surface profile to be scanned. Here, the function principle of the measurement remains unchanged: the position control to the null point of the focus sensor characteristic line (null indicator measuring principle).

However, compared with the focus-stylus-sensor, the sensor design for the focus-AFM-sensor had to be modified so as to enable an efficient application in the NPM-machine. The reason for this is – on the one hand – the design of the cantilever whose mechanical strength is strongly limited due to the tip radius of about 10 nm and the material (silicon). On the other hand, as the positioning table of the NPM-machine has a relatively high weight, it can be moved only in a low-frequency range in order to keep the stylus tip of the AFM in the null point of the focus sensor signal during control. These circumstances restrict the scanning speed to < 1 µm/s.

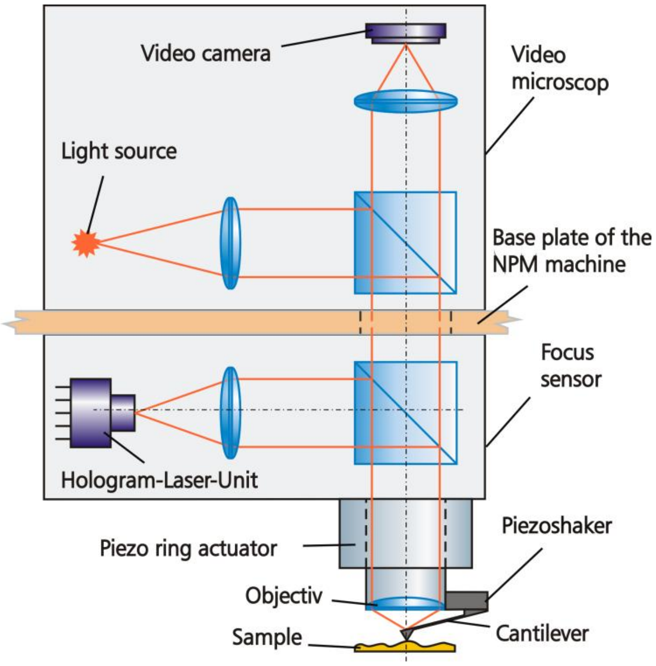

Fig. 3: Basic structure of a focus-AFM-sensor on the basis of the focus sensor

This problem has been solved by inserting an additional piezo element between the focus sensor and the AFM-fixture, which also contains the focus lens. This enables an additional zero position re-adjustment which is of a higher frequency compared with the NPM-machine. During the measurement process, the measuring machine supplies the low-frequency portion of the re-adjustment movement. On the other hand, the piezo element is responsible for the high-frequency portions of this movement as it has a much higher eigenfrequency.

As opposed to the focus-stylus-sensor, the focus-AFM-sensor maintains the functions of the integrated digital camera microscope. It does not only serve for the cantilever-laser beam adjustment, but also for ensuring the almost unrestricted observation function during a measurement.

The single nanosensors (laser focus sensor, focus-stylus-sensor, AFM-sensor) set up on the basis of the focus sensor were then integrated into a motorized turret device, thus enabling an automatic change of the sensors (Fig. 4). For the optical probing, an equivalent LWD-lens having a working distance of 10 mm is used.

2.3 Comparison of the sensors

In the case of the nanosensors set up (focus sensor, stylus sensor and AFM-sensor), a direct comparison of the spatial resolution is possible as the NPM-machine and the focus sensor as base sensor provide for identical boundary conditions. Thus, optimum fields of application for the single sensors can be determined more easily.

The spatial resolutions that can be obtained by the focus sensor, the stylus sensor and the AFM-sensor lie within different ranges (corresponding to micro- and nanometre range), which is due to their respective probing methods. At first glance, the answer is trivial: If the highest lateral resolution is to be obtained, the AFM-measuring principle should be utilized. This is justified in many cases. However, often there are measuring tasks to be carried out which require a lateral submicron resolution which, in turn, can be obtained more easily by means of optical or also stylus measuring techniques. In this case, “more easily” means that the specimen will not be damaged during measurement and that practically no wear and tear of the AFM tip will occur.

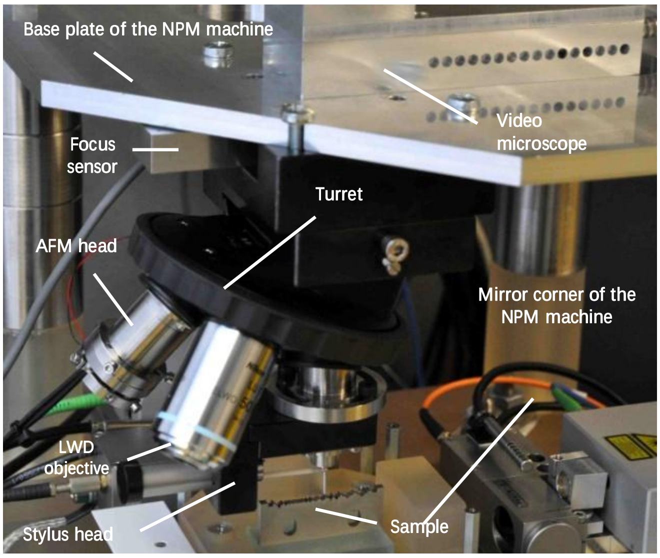

Fig. 4: Nanosensors integrated into a turret system in the NPM-machine

An example proving this is shown in Fig. 5. Here, sections of a glass scale were measured using a stylus sensor, an AFM-sensor and also a focus sensor. This glass scale was manufactured by applying an etching method, which usually involves a certain degree of roughness. Although the focus-AFM-sensor (Fig. 5a) is well able to measure the structure without any problems, it is – due to its nanometre-sized stylus tip - "hypersensitive" to the surface texture at the etched points of the grating.

On the contrary, the focus-style-sensor (Fig. 5b) „smoothes“ the measured values of the etched surface with its large tip radius, thus reproducing the properties of the grating of the scale much more clearly. In this case, the lateral nanometre resolution is guaranteed by the measuring properties of the NPM-machine and the exactly known geometry of the stylus tip. As in general the geometry of the stylus tip is not exactly known, some reliable statements can only be made concerning the grating period (but not concerning half the grating spacing).

Also, a high-precision optical measurement of this glass scale by means of the focus sensor (Fig. 5c) is possible although rough etching points causing complicated diffraction phenomena [3] may falsify the measuring result due the small grating constant. In this case, the grating period can nevertheless be determined with nanometre accuracy.

On the other hand, the measured depth of the structure is found to be completely wrong: about 190 nm instead of 130 nm (cf. stylus or also AFM measurement). The reason for this is that the phase jumps occurring on the elevated chromium layers of the glass scale differ from those occurring on the intermediate etched glass surfaces.

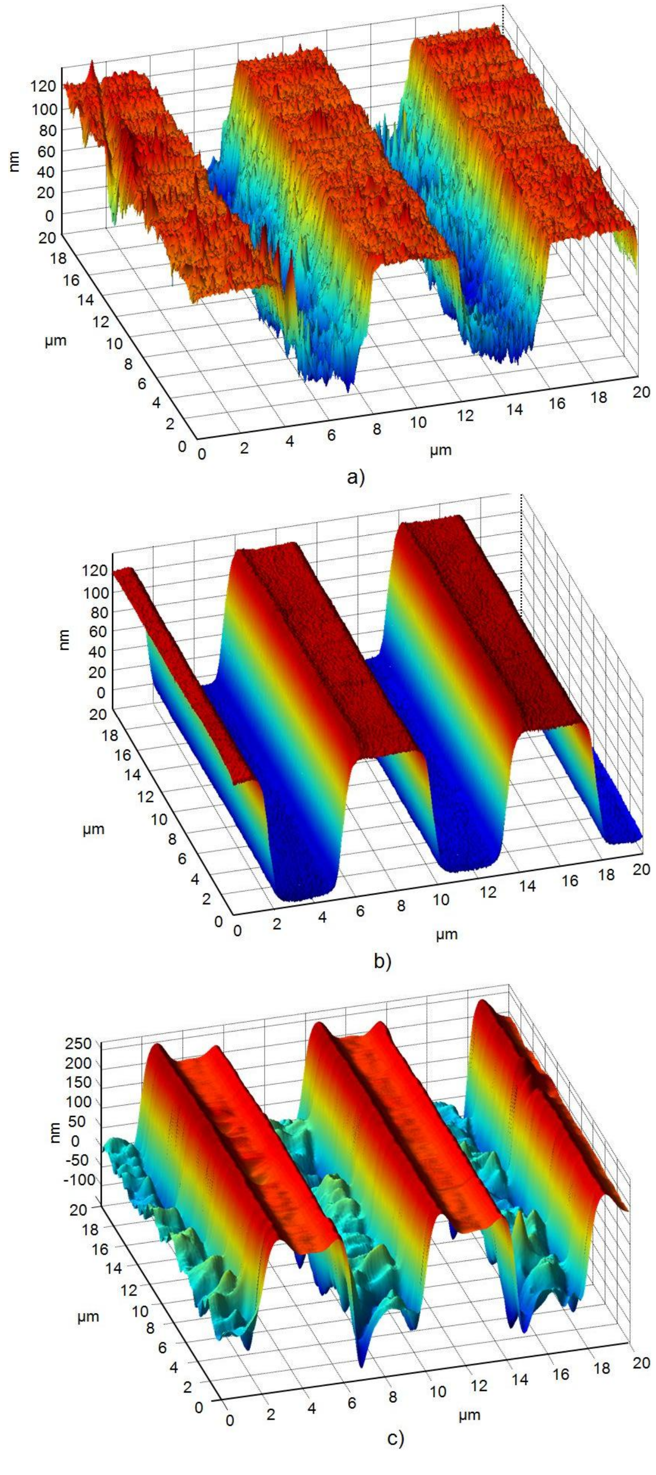

Fig. 5: Measurement of a glass scale using an AFM-(a), a stylus- (b) and a focus sensor (c)

3. IMPROVEMENT OF EDGE DETECTION BY MEANS OF A FOCUS SENSOR

When using a laser focus sensor for edge detection in the nanometre range, the so-called "Bat-Wing-effect" [3] (Fig. 6) is generated due to diffraction. This effect can very well be reproduced at nanometre accuracy. According to earlier investigations, the distance between two edges can be detected with an extended measuring uncertainty of < 8 nm [4]. However, the absolute edge position can be determined only vaguely due to the diffraction-limited spot size.

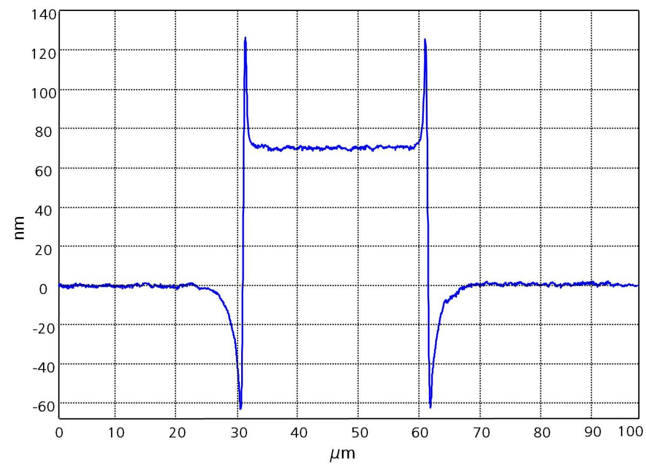

Fig. 6: Bat-Wing-effect on edges of a step height

In an indirect way, however, it is possible to determine the spatial resolution or also the edge position through some kind of „optical unfolding" of the result of measurement, which can be realised by means of appropriate algorithms. This was implemented through the adaptive application of the rigorous theory of diffraction [5]. Due to its robustness and universality, the "Rigorous Coupled Wave Method" (RCWA) has proved to be optimum. The simulations have been verified by means of AFM-measurements as a reference. The advantage of the laser focus sensor over previous approaches of edge correction is that also the step height of the structures is determined with nanometre accuracy directly during the measurement because the sensors are integrated in a turret system.

If the geometrical step width is known from the AFM measurement, the difference of the step width measured by the focus probe can be determined. To this end, either the convolution of the AFM tip and the structure must be estimated in order to determine the geometrical step width from the AFM measurement or the tip must be calibrated from measurements on a step width standard.

In the case of the optical probing of structures with different materials (also transparent ones) such as Si and SiO, phase errors result which falsify the results of measurement. The above-cited RCWA method has already been applied in the case of material combinations with transparent materials, showing a good qualitative agreement with practical measurements.

The results of AFM and focus probe measurements (Fig. 7) demonstrate the agreement between simulations and current measurements of the deviation between the optical and the geometrical edge position. Both curves show a

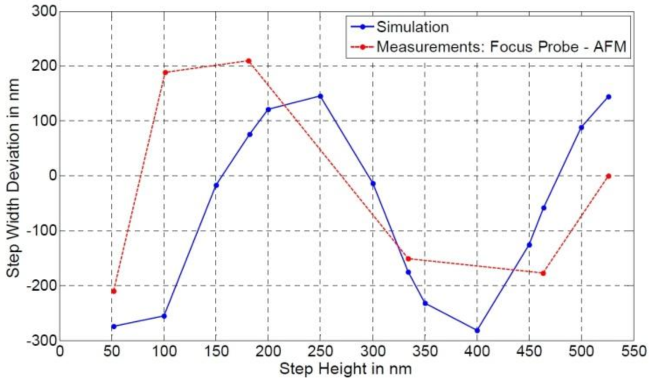

Fig. 7: Measurement results versus simulation. The step width deviation versus step height is shown. The reference for the simulation is the input profile whereas for the focus sensor measurement an AFM measurement was used.

qualitatively similar distribution in their periodic progression. The mean deviation between the measurement and the simulation is about 150 nm, which - compared with the uncorrected measurements of about 600 nm (laser spot size) - represents a clear improvement.

The differences observed are probably due to insufficiencies in the modelling of the detector, deviations from the assumed ideal binary specimen profile and rough surface scattering effects. Moreover, the accuracy of the AFM reference is questionable itself. Nevertheless, we have shown that it is in principle possible to correct the position of an “optical edge” through the application of rigorous modelling utilizing a priori knowledge of the step height of the specimen. One of the outstanding advantages of the focus probe is the high accuracy in the step height measurement. Therefore, this parameter can be directly used in the model. This is the first step towards the improvement of optical edge detection using a combination of optical measurements with a focus probe and its simulation based on rigorous diffraction theory. We could demonstrate a correlation between step height and the overshooting effect of optical sensors. Our results show that the new approach makes a systematic correction of the optical edge measurement possible through the determination of the FWHM (full width at half maximum) for known step heights [6].

4. LITHOGRAPHY WITH THE FOCUS SENSOR

Due to its outstanding metrological features, the NPM-machine offers a number of unique possibilities of generating and processing precision structures with nanometre precision. One of these possibilities is the lithographic process.

At the present moment, it is not possible to apply lithography in a relatively easy manner to curved surfaces as distortions usually result due to the different distances between the mask and the surface. In the case of curved surfaces, a distortion of the light beam would occur, thus leading to defective structures. In such cases of applications, it would thus be advantageous to avoid a distortion of the light beam by shifting the object in normal vector direction of the surface.

Based on those grounds, a lithography unit was developed and implemented in the NPM-machine as the focus sensor contained in the machine allows lithographic structures to be put without distortions for example on lenses. This unit has been integrated in the illumination light path of the camera microscope. It contains an optical fibre coupling of a laser diode with enclosing collimation of the laser light.

In our case, the way the lithographic process functions can be called as "Scanning lithography". Here, the focus sensor operates quite normally in the scan mode, keeping the coated surface in focus. At the same time, the process of exposure is realised by feeding the illuminating laser light into the same measuring objective. It is important to make sure that the wavelengths of the focus sensor and of the lighting unit are chosen as a function of the type of coating used (in our case 650 and 405 nm, resp.).

Thus, due to the freedom of movement of the NPM-machine, any surface structures up to 25 x25 mm² and an inclination up to 20° can be generated.

As an example of the application of lithography on curved surfaces, we want to present the development and production of a series of marker structures for the alignment and position reference of optical surfaces. The markers developed at the Institute of Process Measurement and Sensor Technology of the Technische Universität Ilmenau are supposed to be suitable for most of the topography metrology technologies for optical surfaces. Every marker consists of a set of thin metal coatings and has been produced in collaboration with the Centre for Micro- and Nanotechnologies (ZMN) in Ilmenau.

For the control of the NPM-machine, numerous tests have been developed to produce various structures with well-defined properties. After having successfully applied markers to the surface (a glass lens), see Fig. 8, the qualities of the shapes have been inspected and important properties have been measured and analyzed.

Furthermore, a well-known problem arising during the optical probing of tilted surfaces is the systematic angle-dependent shift of the zero of the focus sensor. This also means that the structures which are generated through lithography with focus sensor are afflicted with systematic deviations from the lateral position. In order to be able to determine the size, the amount and the reproducibility of those deviations more exactly and to find ways to compensate for them, some further detailed investigations will have to be carried out in the future.

5. SUMMARY AND CONCLUSIONS

Optical measuring techniques are of great importance for micro- and nanotechnologies, particularly also for precision measuring instruments up to nanomeasuring technology. At the Institute of Process Measurement and Sensor Technology of the TU Ilmenau, a laser focus sensor presenting excellent metrological properties has been developed which – combined with a nanopositioning and nanomeasuring machine - allows a big variety of different applications.

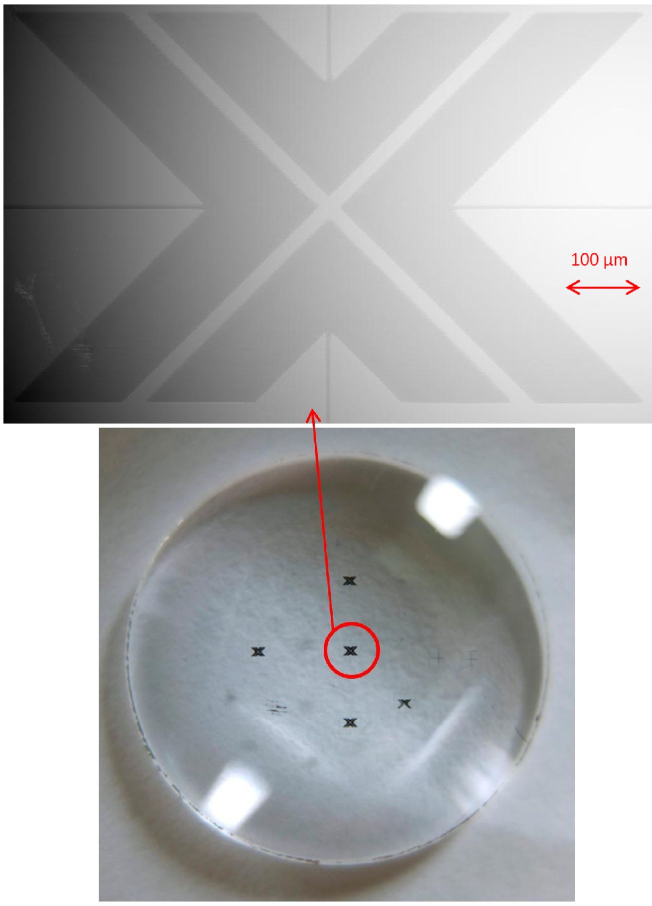

Fig. 8: Marker structures on a lens applied by lithography with the focus probe

On the basis of the laser focus sensor, mechanical-tactile nanosensors (stylus and AFM) have been developed and built. Here, the deflection of the probing measuring tip (stylus or also cantilever) is recorded in a contactless manner with the focussed laser beam of the focus sensor.

The sensors developed have been optimized and linked with each other for a multisensor application. In doing so, optical and mechanical probing methods and, thus, different interactions taking place between the object to be measured and the sensor have been combined in an automatic alternating system, which is absolutely necessary for solving today's tasks of modern surface measuring technology in the nanometre- and subnanometre range in order to achieve a high versatility and good reliability of the measurement results.

A number of comprehensive studies have proved the excellent metrological properties of the nanosensors. At the same time, their limits of application have been revealed but also numerous new challenges, tasks and goals with view to a further optimisation and improvement of the sensors.

In addition, we have shown that edge detection in the case of the 3D-measurement of microstructures with laser focus sensors can be improved if it is possible to predict and also compensate for any undesired diffraction effects through exact simulations of the signal to be expected. For this purpose, a simulation method based on a combination of a physical-optical model for describing the light propagation in the excitation and detection ray path of the sensor optics including the modelling of the optical signal on the sensor with the Rigorous Coupled Wave Approach (RCWA) for describing the diffraction of the light beam falling on the edge structure has been developed.

Moreover, we have shown the possibility of using the laser focus senor not only for precision measurements, but also for the direct generation of precision nanostructures by means of lithography. Here, compared with classical lithography the goal is to ensure the capability of processing free-form structures on tilted surfaces. For example, we have successfully produced marker structures for the alignment and position reference on a glass lens.

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