

High Precision Freeform Polymer Optics

Optical freeform surfaces – increased accuracy by 3D error compensation

●▶ **Injection molding offers a cost efficient method for manufacturing high precision plastic optics for high volume applications. Beside classical optical surfaces like planes, spheres and also aspheres the demand for surfaces without symmetric properties, so called freeform surfaces, continues to rise. To push the surface accuracy for high volume applications for the molded freeform lens, new 3D iteration cycles to compensate systematically residual errors have to be developed. This paper will illustrate a new way for the manufacturing of ultra precision mold tool inserts with submicron precision and show the manufacturing of replicated freeform surfaces with micrometer range shape accuracy at diameters up to 40mm. Furthermore, two examples for molded, energy and material efficient freeform optics adapted to the green photonics philosophy are shown and explained.**

Modern optical systems applied to key optical markets such as mobile communication, healthcare, sensoric, security, lighting and also photovoltaic's need to have more complex optical surfaces to achieve enhanced performance requirements and / or reduced installation space. One possibility to achieve these challenging goals is the application of freeform surfaces within the optical system. Powerful mathematical algorithms and design tools allow the design of freeform surfaces [1, 2]. Such novel optical design surfaces strongly encourage the development of manufacturing methods. Specifically new surface descriptions without an axis of symmetry, new ultra precision machining methods and unsymmetrical shrinkage compensation strategies have to be developed to produce freeform optical surfaces in a high precision for high volume applications. Products like head mounted displays (HMDs), head up displays (HUDs), detector elements or also innovative LED illumination optics require freeform optics

to guarantee an excellent function [3–6]. For the manufacturing of high volumes and acceptable costs, high precision replication techniques like injection molding can be used.

This article will illustrate an efficient way for the manufacturing of mold tool inserts with submicron precision and show the manufacturing of replicated freeform surfaces with micrometer range form deviation at diameters up to 40mm with a surface roughness of about 2nm. In addition to that, two different applications in energy efficient illumination of structures and high homogeneity realised by optical freeform surfaces will be shown.

In terms of green photonics, an input for realising high precision, energy and material efficient optical systems is given by this new process chain.

Process chain for manufacturing high precision freeform optoelectronic systems in high volumes

For high volume applications, injection molding offers a cost efficient method for manufacturing high precision plastic optics. In general the process steps for manufacturing a freeform optical systems are analogue to realizing rotational symmetric optical systems what is well known. The difficulty on freeform surfaces is to handle the 6 degrees of freedom in all process steps beginning from the design up to the system integration. The typical process steps to realize optoelectronic systems is shown in Figure 1.

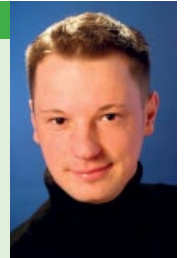
The basic elements for realizing high precision freeform optical components in high volumes are the tooling and the injection molding process. Also measurements and data handling between iteration cycles are very essential to push the precision. With respect to the optical performance of plastic optics, properties of the raw material must be considered such as the molecular structure, the molecular conformation and impurities. Today the materials most commonly used for molding plastic optics are PMMA (poly-

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methylmethacrylat), PC (polycarbonate), PS (polystyrol), COP (cycloolefin poymer) and COC (cycloolefin-copolymer) [7].

Exemplary freeform optical element for process evaluation

For analysing the whole process chain of injection molding freeform surfaces including novel correction strategies, an exemplary freeform surface has to be defined by a mathematic equation. Main applications described in the introduction effort continuous freeform surfaces with low frequent deviations. In searching for such a freeform surface an exemplary Zernike polynomial function was found (3D view see Figure 2a, Equation, see bottom of next page).



FIG. 1: Process chain for realizing optoelectronic systems in high volumes.

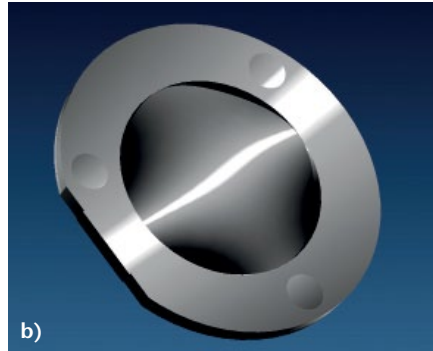
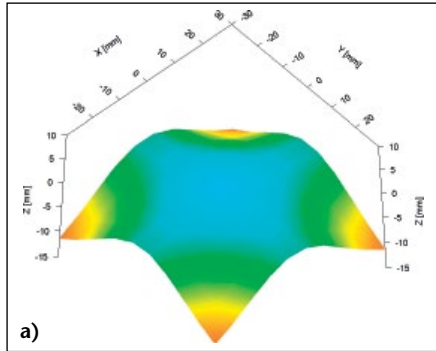


FIG. 2: a) Designed freeform surface for developing the process chain; b) Designed optical element for injection molding in 3D CAD.

FIG. 3: Machined mold positioned at the ultra precision machine.

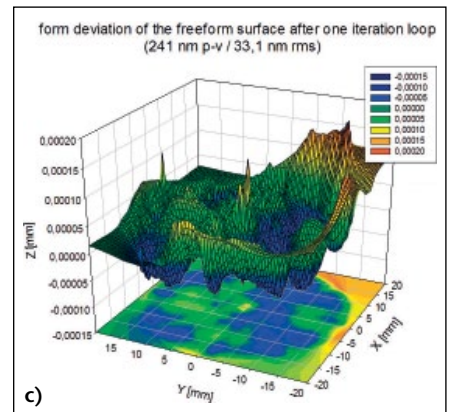
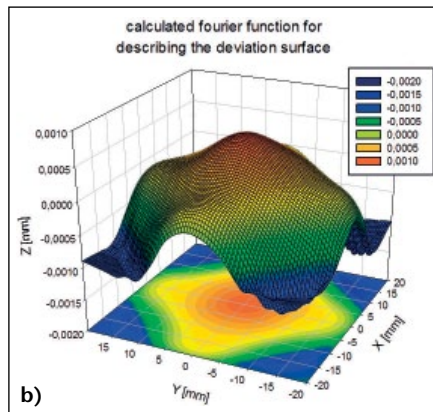
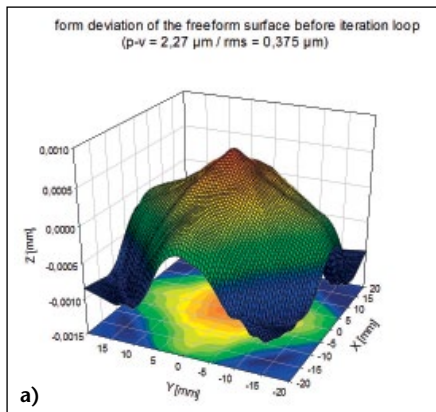


FIG. 4: a) Surface deviation at the mold before iteration loop, 3D view; b) Calculated Fourier function as error description of the surface deviation; c) Surface deviation at the mold after one iteration loop, 3D view.

Within the Cartesian coordinates (x , y , z), z is the sag at a defined x and y position. The non rotational symmetric term (Z_{nrs}) is described by the $Z_{Zernike}(4,4)$ term with 0,2, normalised to a radius of 20mm. The $Z_{Zernike}(4,4)$ term describes a so called "Tetrafoil" from the defined Zernike series. The rotational symmetric part (Z_{rs}) is a convex sphere with a radius of $R = 100$ mm.

The deviation of the non rotational symmetric part is 1.26mm at the clear aperture diameter of 40mm. At the pitch circle in the outer area 3 spherical elements are po-

sitioned that provide an optional referencing of the freeform surface in the measurement or the optical system.

The designed freeform surface has to be implemented into an optical volume element what is dedicated for the molding process. For this freeform lens, the gate position can be seen in Figure 2b and a bevel at the outer diameter was added for manufacturability. The outer diameter of the part is 70mm and the center thickness is 5.5mm. The material for the lens is PMMA 7N.

Ultra precision manufacturing and error correction of the freeform optical surface at the mold

For manufacturing the freeform optical mold, ultra precision machining methods utilizing a monocrystalline diamond tool as explained in [8] and [9] are preferred methods for an efficient machining. The surface explained above was designed for the slow tool servo-technology. This process is qualified for generating smooth freeform surfaces where the 2 axis diamond turning machine is modified with a CNC controlled rotation axis (c) in addition to the 2 linear axis (x and z).

The defined Zernike surface was at first manufactured at the mold best possible like the process state of the art. The tool insert is a hardened steel substrate added with a special nickel phosphorous plate with a

$$Z_{freeform}(x, y) = Z_{nrs}(x, y) + Z_{rs}(x, y) = z_{Zernike}(4,4) \cdot \sqrt{10} * \left(\frac{\sqrt{x^2 + y^2}}{20} \right)^4 \cdot \cos(4 * \arctan\left(\frac{y}{x}\right)) + \frac{\frac{1}{R} \cdot (x^2 + y^2)}{1 + \sqrt{1 - \left(\frac{1}{R}\right)^2 \cdot (x^2 + y^2)}}$$

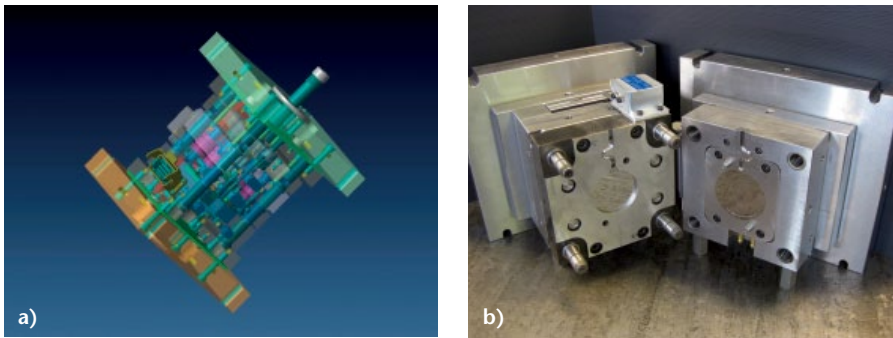


FIG. 5: (a) 3D CAD design of the injection mold; (b) Manufactured injection mold.

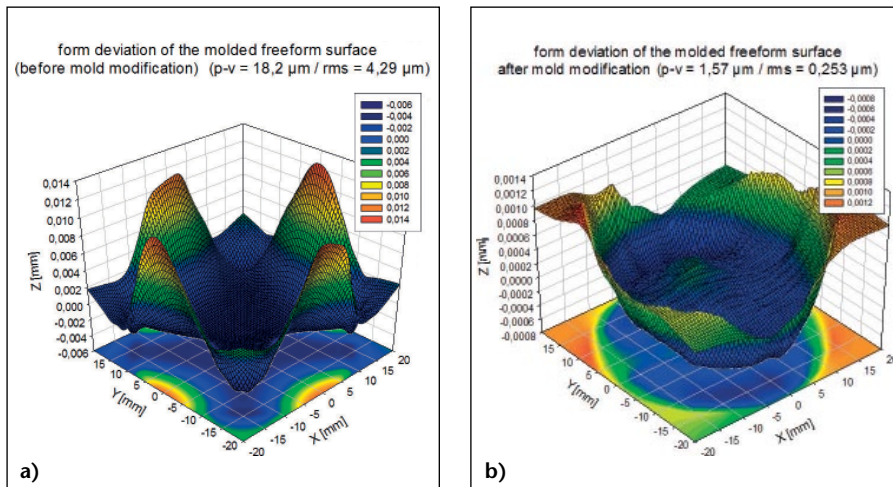


FIG. 6: Form deviation of the molded freeform surface a) before and b) after 3D iteration loop, 3D view.

phosphorous content of $>10\%$ for an efficient diamond machining process, where roughness's $R_a < 5 \text{ nm}$ can be achieved [7].

The machined mold insert was measured with the high accuracy profilometer Panasonic UA3P-5. The measurement accuracy for this kind of freeform surface (size, slopes) is better than 50 nm [10]. The measured surface data were subsequently evaluated as explained in [11]. A surface accuracy with $2.27 \mu\text{m}$ p-v and $0.375 \mu\text{m}$ rms (root mean square) was measured at a clear aperture diameter of 40 mm (Figure 4a).

To achieve a much higher precision at the mold-freeform surface, a special iteration loop was developed. Fitting the deviation surface by a Fourier equation (Figure 4b) with a coefficient of determination $r^2 = 0.9969$ to the measured data, the deviation surface can be superimposed to the well Zernike surfaces where a new freeform surface can be calculated with a very high numerical precision. After generating a new tool path, the freeform mold was generated where all the other technological process

parameters have to be strongly the same as the first machining. After one iteration loop, the form deviation was minimized from $2.27 \mu\text{m}$ p-v ($0.375 \mu\text{m}$ rms) down to $0.24 \mu\text{m}$ p-v (33.1 nm rms) which is nearly one order of magnitude (Figure 4c).

Injection molding of high precision freeform surfaces with use of the developed iteration loop

A main element for the injection molding process is the mold. For practical experiments, the cavity as well as the complete injection mold was designed and manufactured. The classical configuration with the so called nozzle and ejector side can be seen at the 3D CAD model (Figure 5a) as well as the manufactured tool (Figure 5b).

According to [12], the quality of molded parts is a result of a complex combination of the used material (according their pVT-characteristics), the part and mold design as well as the process conditions. Thereby shrinkage is one of the several important factors affecting the quality of the molded

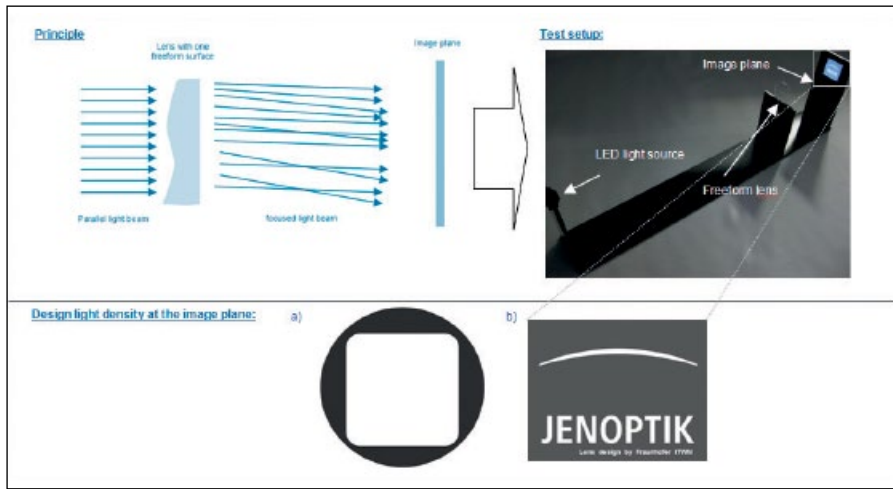


FIG. 7: Principle and test setup for freeform optics with the function of directed illumination.

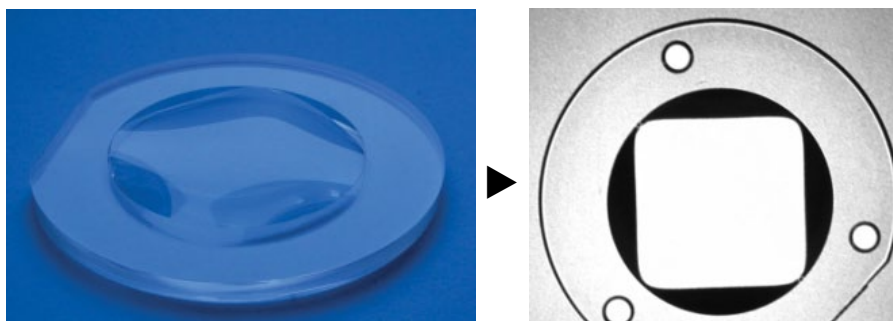


FIG. 8: Molded freeform optic with Zernike freeform surface and the function.

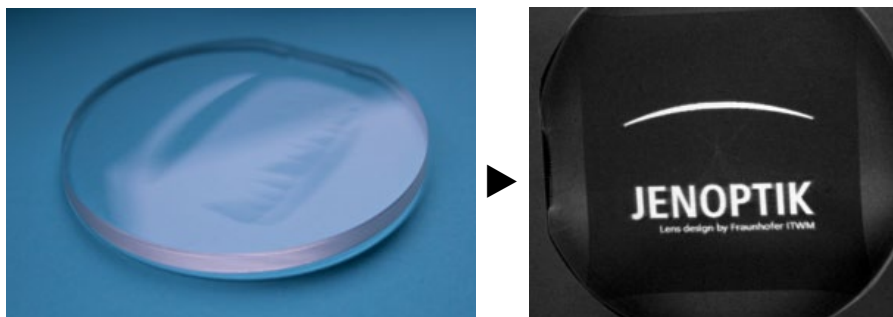


FIG. 9: Molded optic with JENOPTIK freeform surface and the function.

part. Process parameters like packaging pressure, dwell pressure, dwell pressure time, melt temperature and tooling temperature as well as cooling time have an influence, shown in [13].

Measuring some molded freeform surfaces like explained for the measurement at the tool insert a stable version was found with a process random error of $1.38\mu\text{m}$ p-v and a p-v value of about $18\mu\text{m}$ respectively $4\mu\text{m}$ rms (see Figure 6a). To multiple the precision of the defined freeform surface, further process steps are required strongly. For this the measurement of the surface deviation at the molded part has to be described by a mathematical function. Following a new freeform surface for the mold can be calculated where the deviation of

the molded freeform surface has to be superimposed to the Zernike sag itself at the tool insert. The new calculated surface comprises all the information which controls the systematic shrinkage effect of the molding process. Molding the defined Zernike freeform optic again with the same molding process parameters but the modified tool insert, the molded freeform lenses were measured. A form deviation of about $2\mu\text{m}$ p-v and $0.28\mu\text{m}$ rms was reached by one iteration cycle which is more than one order of magnitude better. One measurement with $1.57\mu\text{m}$ p-v and $0.253\mu\text{m}$ rms can be seen in Figure 6b. The p-v value occurs at the outer area, the middle area is very even. For example at a diameter of 22mm , a p-v value of $< 0.5\mu\text{m}$ was reached reproducibly.

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Beside the form accuracy of optical surfaces, the micro roughness is a main quality factor. To check the roughness at the defined Zernike freeform surface after diamond processing and injection molding, some measurements at a white light interferometer were done. In result a roughness of 2.40nm in R_a at the diamond turned mold and 1.99nm in R_a were measured.

Examples of molded freeform optical elements

Understanding the process chain for molding freeform optics in a very high precision, some applications will be shown. For this, 2 applications for directed illumination will be explained. As shown in Figure 7, a parallel light beam can be an input for the freeform lens. The modified parallel light beam by the one freeform surface at the lens will generate a special light density distribution at the image plane. In a first case of the Zernike optic, a quadratic, homogeneous field with round edges has to be seen as shown in the design. In a second case, a logo with a tiny sentence has to be seen. For this lens, the design was done by the Fraunhofer ITWM.

Freeform element for shaping a quadratic, homogeneous illuminated light field with rounded corners

- The Zernike freeform optic has the function for focussing a parallel light beam to a quadratic (rounded corners), homogeneous light field within the clear aperture of 40 mm. The measured homogeneity of the brightness and the contrast in the rectangular area can be seen in Figure 8. In the outer area, the transmission through the plane surfaces and the reference spheres can be seen.

Freeform element for shaping a logo with even tiny letters

- The molded freeform optic for shaping the JENOPTIK Logo can be seen in Figure 9. Here the parallel light beam is formed that the JENOPTIK Logo and the tiny sentence "Lens design by Fraunhofer ITWM" underneath can be seen at the image plane. Looking at the molded lens, the JENOPTIK Logo can already assumed.

Conclusions

Freeform optical surfaces are currently a big challenge in the field of modern optic applications. For a high volume market, injection molding is the manufacturing method of choice for cost efficient and high precision freeform optics. To push the accuracy of the freeform surface at the molded lens compared to the state of the art, the accuracy at the mold has

to be increased and an efficient 3 dimensional shrinkage compensation strategy is necessary. The article discussed a process chain for producing ultra precision freeform optical surfaces at the mold and at the molded lens as well as novel material and energy efficient applications. With each additional process step, the accuracy increased within one order of magnitude. With the novel process chain, freeformed shape deviations have been successfully minimized to 0.24 μm p-v at the mold and to about 2 μm at the molded freeform surface at a diameter of 40 mm. In addition to that, two actual examples illustrate the excellent function of the freeform optical elements for directed illumination manufactured by injection molding. The accuracies show that some imaging applications also can be realized by the process chain shown.

Future activities will concentrate on improvement of process stability and further pushing the accuracies of molded surfaces for high end applications of plastic optics.

Acknowledgments

Some elements of the presented research work are funded within the FREE project by the Federal Ministry for Education and Research, (Grant No. JENOPTIK Polymer Systems GmbH: 13N10826). The author thanks a lot for this kind possibility for efficient research. Also the author thanks the Fraunhofer ITWM for the given design data of the JENOPTIK freeform surface and the Fraunhofer IOF within the general support.

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