Diamond milling or turning for the fabrication of micro lens arrays: comparing different diamond machining technologies

Scheiding, Sebastian, Yi, Allen, Gebhardt, Andreas, Loose, Roman, Li, Lei, et al.

Sebastian Scheiding, Allen Y. Yi, Andreas Gebhardt, Roman Loose, Lei Li, Stefan Risse, Ramona Eberhardt, Andreas Tünnermann, "Diamond milling or turning for the fabrication of micro lens arrays: comparing different diamond machining technologies," Proc. SPIE 7927, Advanced Fabrication Technologies for Micro/Nano Optics and Photonics IV, 79270N (14 February 2011); doi: 10.1117/12.874751

SPIE. Event: SPIE MOEMS-MEMS, 2011, San Francisco, California, United States

Diamond milling or turning for the fabrication of micro lens arrays: comparing different diamond machining technologies

Sebastian Scheiding[1,3], Allen Y. Yi[2], Andreas Gebhardt[1], Roman Loose[1], Lei Li[2], Stefan Risse[1], Ramona Eberhardt[1] and Andreas Tünnermann[1,3]

[1] Fraunhofer IOF - Institute for Applied Optics and Precision Engineering, Albert-Einstein-Str. 7, D-07745 Jena, Germany;
[2] The Ohio State University, Industrial and Systems Engineering, Columbus, Ohio, USA;
[3] Friedrich Schiller University Jena, Institute of Applied Physics, Albert-Einstein-Str. 15, D-07745 Jena, Germany

ABSTRACT

Diamond-micro milling and ultra-precision free-form turning technologies for fabricating micro lens arrays (MLA) with a large number of lenslets are explained in detail and compared. Besides the programming of the toolpath, correction loops and cutting parameters are presented. Both technologies are compared regarding achievable form deviation, roughness and economic factors like machining time. The paper offers a guideline for ultra-precision machining of micro lens array master molds on planar substrates and curved surfaces.

Keywords: Micro Lens Array, Diamond-Micro Milling, Free-form Machining, Fast Tool Servo, Wafer Level Manufacturing, Diamond Turning, Mold Insert, Micro Optics

1. INTRODUCTION

Micro lens arrays containing a large number of lenslets with aspheric shape and a precise position are used for beam shaping, illumination or as imaging optics in sensor devices and cameras. The geometry of micro lens arrays is tailored to the purpose of the optical element in the application. Depending on the size, the substrate material and the number of lenses in a certain area, the fabrication approaches are either based on lithographic technologies or machining processes with diamond tools. For each optical design, a suitable manufacturing strategy has to be chosen.

Wafer scale manufacturing of small optics is a high volume fabrication method for low-cost optics. Its fundamental principle is the sandwich-like assembly of the light sensitive electronics and optical components such as lenses and mechanical components such as apertures and spacers on the wafer level. After joining all components the dicing results in a batch of wafer level cameras for use in cellular phones or other consumer electronic devices. The fabrication of mold masters for the high-volume replication is challenging due to the high demands on the optical quality of the relatively deep aspheres and the precise spacing on wafer sizes up to 300 mm.

Micro lens arrays are also a centerpiece of today's sensor products, either to raise the fill factor and collect more light on each pixel or to deflect the incoming beam to measure the aberrations of the wavefront, the working principle of the Shack-Hartmann sensor. Within illumination optics, micro lens arrays are commonly used for beam homogenization in projection systems. In all fields of application ranging from automotive, medical, consumer and industrial optics to high end sensors for space instrumentation, high quality lens arrays for direct use or replication have to be fabricated.

Requirements on the allowable shape irregularities are ranging between $\pm 3\%$ of the Radius of Curvature (ROC) for illumination optics to 200 nm (p-v) for diffraction limited imaging optics. Besides the form of an optical surface, its microroughness is of high importance. Scattering losses and blurred images can be avoided if the surface finish is adequate to the wavelength of the transmitted light. Optical elements for imaging purposes in the visible spectral range shall be finished with a micro roughness lower than 5 nm (rms).

Further author information:
Sebastian Scheiding: E-mail: sebastian.scheiding@iof.fraunhofer.de, Telephone: +49 (0)3641 807 353
Allen Y. Yi: E-mail: yi.71@osu.edu, Telephone: +1 (614) 292-9984

Advanced Fabrication Technologies for Micro/Nano Optics and Photonics IV, edited by Winston V. Schoenfeld, Jian Jim Wang, Marko Loncar, Thomas J. Suleski, Proc. of SPIE Vol. 7927, 79270N · © 2011 SPIE
CCC code: 0277-786X/11/$18 · doi: 10.1117/12.874751

2. LITHOGRAPHIC TECHNOLOGIES

A variety of micro technology manufacturing methods can be used for MLA structuring. Lithographic approaches with a subsequent reflow process, laser lithography, UV-curing of resin droplets and step- and repeat molding of polymers are state of the art processes for the master manufacturing. The lithographic approach is based on exposing and developing resist columns on aperture stops and pedestals on a planar substrate.[1] Therefore, the resulting profile is determined by the shape of the lens' footprint and the volume of the resist to be melted. In case of the most relevant rotationally symmetric lenses, the footprint of the lens is a circle and the resulting geometry a sphere due to the surface tension of the liquid melt. Another method to manufacture very similar MLAs with spherical or slightly aspherical lenslets is to apply a number of liquid resin droplets on a substrate. The wetting angle, the volume of resin and the gravitation can be used to shape the lenslets. The subsequent UV-exposure cures the resin droplets to their final form due to volume loss from the polymerization shrinkage. More design freedom offers laser lithography, which is a direct writing technique that enables the generation of free-form profiles, not limited to spherical shapes on planar substrate surfaces.[2] Here, a laser beam is scanned over a photo resist layer while the intensity of the beam is modulated. The height of the resulting profile at a given position is determined by the local dosage of the writing beam. However, the technology is limited to structures of several ten micrometers in height.

All technologies of this kind have in common that a large number of lenslets can be manufactured. Lenses that are shaped in a liquid phase offer an excellent surface quality. On the other hand the surface figure and the design freedom regarding aspheric or free-form surfaces are process limited and can only be guaranteed by direct writing technologies such as laser lithography. Major drawbacks of the lithographic approaches are the limited lens depth and degree of aspherization. The shrinkage of the polymer lenslets during the curing process causes a shift of the focal length in the ‰ to the % range. The volume loss increases with the size of the lenslets and limits the use of lithographic or dosing technologies for imaging optics with high resolution.

Furthermore a high fill factor with intersecting lenses is not feasible due to the minimization of surfaces of the resin in the liquid phase. Nevertheless, these techniques are proven tools for a wide spread field of applications.

3. OVERVIEW OF THE MACHINING TECHNOLOGIES

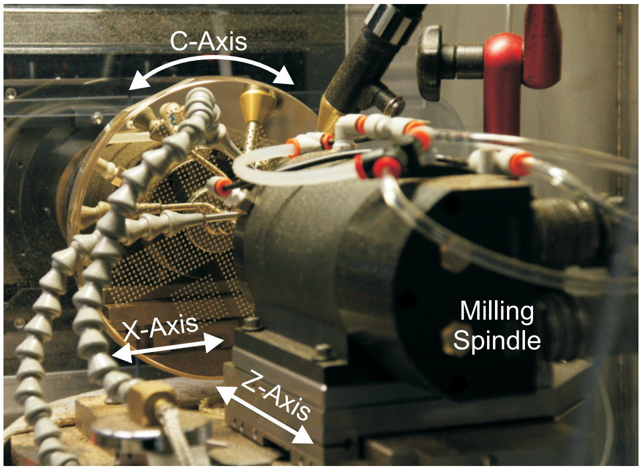
Besides the above mentioned technologies, precision machining of arrays or master arrays for replication is emerging into the market for its potential to fabricating structures truly aspheric or free-form lenslets. The feasible geometries depend on the shape of the cutting edge of the diamond tool tip and the kinematics of the machining process. The smallest possible radius of curvature is a few hundred microns. The micro lens arrays can be very dense or even contain overlapping lenslets. The ultra-precision machining thus is an adequate addition to lithography for structuring three-dimensional microoptics in the mesoscopic scale.

Either ultra-precision free-form turning technologies or diamond micro-milling (DMM) are appropriate manufacturing methods to fabricating complete monolithic lens arrays. The chipping is based on cutting with a hard and geometrically defined diamond cutting edge, which is fed into the softer material. Both machining techniques employ a mono-crystalline diamond tool, whose cutting edge waviness is in the range of below 250 nm. Non ferrous metals such as aluminum, brass, copper and their alloys are machinable. In addition plastics and some crystals can be chipped with diamond tools. Differences between diamond turning and micro-milling include machine kinematics and the generation of the cutting speed. Whereas the cutting speed is generated from the rotating workpiece in turning applications, the cutting speed results from the rotating tool in micro milling.

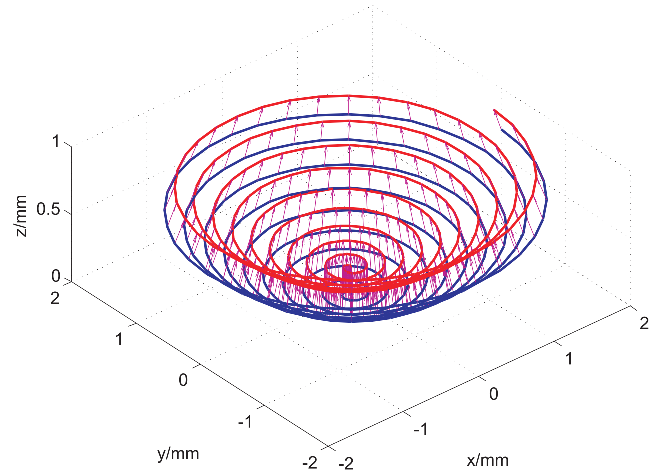
Diamond Micro-Milling processes can also be realized on the more commonly used ultra-precision turning machines with a high-speed spindle addition. The work piece positioning and feed is realized using the polar axis as described in Scheiding et al.[3] A comparison of free-form machining techniques in production of monolithic lens arrays is presented by Davis et al.[4] That publication focuses on the machining of a small number of relatively large lenses in germanium.

4. DIAMOND MICRO-MILLING

The diamond ball end mill rotates about its axis with high speed and removes µm-sized chips. The high speed milling spindle used is a temperature controlled air bearing spindle with error motion in the nm range. Three machine axes are used to position the tool relative to the substrate and to feed the tool along its spiral tool



(a) Machine setup for micro milling of lens arrays



(b) Tool radius compensation for the micro milling of an aspheric lenslet

Figure 1. Micro milling of lens arrays

path. Possible machine kinematics are a Carthesian alignment or a polar alignment of the axes. In case of a polar turning machine these axes are two linear axes (X, Z) and one rotational axis (C) as shown in figure 1. In contrast to conventional diamond turning, the rotational axis is operated discontinuously in C - axis mode. It can be positioned like a rotary table to arbitrary angles. Each lenslet is machined individually. Systematic errors resulting from a misalignment of the toolshaft to the spindle axis or the waviness of the diamond ball end mill can be corrected using a correction cycle. The studies were conducted on a Nanoform 250 from Precitech Inc. with an additional B-Axis and ISO 2.25C spindle from Professional Instruments.

4.1 Programming

Although the MLA is machined on an ultra-precision turning machine, the small off-axis lenslets are not rotationally symmetric to the center of the rotary axis. Hence the MLA has to be handled like a free-form surface regarding operation mode and commands. The tool center points are derived from the 3D surface information of the design asphere and the radius dimension of the diamond tool tip, considering the slope of the lenses. The programming of the numeric control is based on the calculation of nodes on a spiral tool trajectory on the aspheric surface. The surface pointing vector of a central aspherical lens can be described in Cartesian coordinates as:

$$\vec{r} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x \\ y \\ \frac{x^2+y^2}{R\cdot\left(1+\sqrt{1-(1+\kappa)\cdot\frac{x^2+y^2}{R^2}}\right)} + A_4\cdot(x^2+y^2)^2 + A_6\cdot(x^2+y^2)^4 + A_8\cdot(x^2+y^2)^6 \end{pmatrix} \tag{1}$$

Here R is the radius of curvature at $x = y = 0$, κ is the conic constant and A_4 to A_8 are the aspheric coefficients. The cross product of the partial derivatives $\frac{\partial \vec{r}}{\partial x}$ and $\frac{\partial \vec{r}}{\partial y}$ of the surface is the normal vector $\vec{N}$.

$$\vec{N} = \left(\frac{\partial \vec{r}}{\partial x} \times \frac{\partial \vec{r}}{\partial y}\right) = \begin{pmatrix} -\frac{\partial z}{\partial x} \\ -\frac{\partial z}{\partial y} \\ 1 \end{pmatrix} \tag{2}$$

The normal vector $\vec{N}$ of a surface node is used to calculate the offset for the tool radius correction as illustrated in figure 1(b). The command set of each lenslet contains the shifted tool center point of each node. The resulting machine program for the whole array sums up the cutting data of every lens in the array and additional information about speeds and feeds. The typical file size is around 1.5 MB per lenslet. The motion

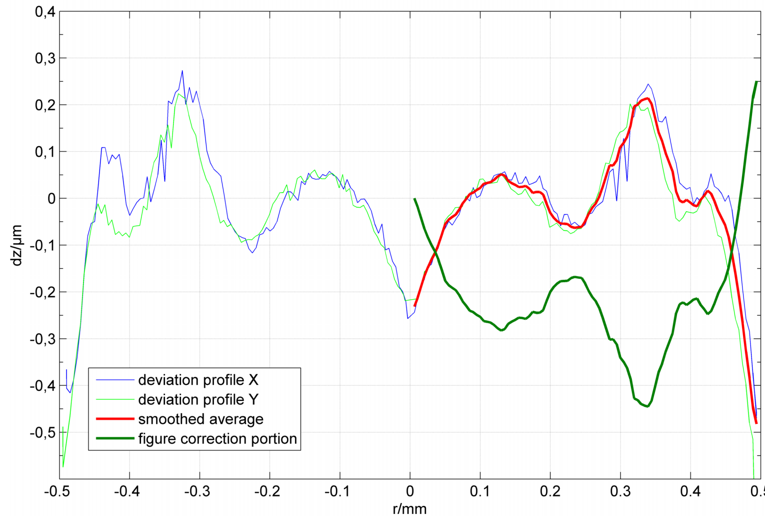


Figure 2. Error profile of an aspheric lenslet measured with a Ultra High Accuracy 3D Profilometer UA3P by Panasonic. Smoothed average of the profile is used to calculate the correction path for a figure correction.

of the machine during the cutting process is a slow and harmonized oscillation of the linear (X) and the rotary (C) axis, while the linear feed-axis (Z) plunges the tool into the material.

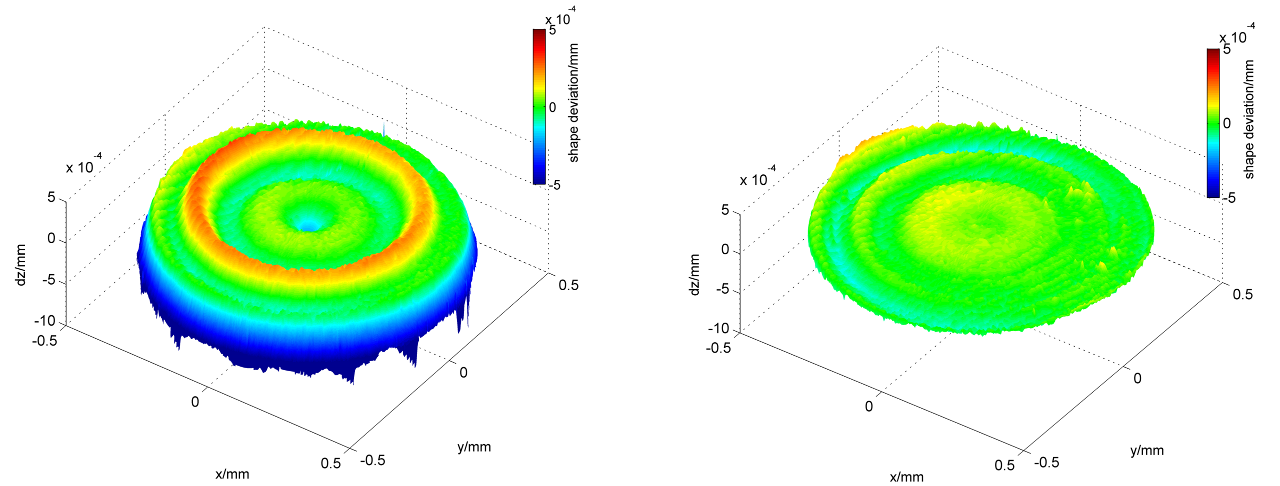
4.2 Form error correction

Essential for achieving a form accuracy in the sub µm-range is the programming of the exact radius of the ball end mill and a correction of the waviness of the cutting edge as well as the kinematical behavior of the machine setup. In the case of a polar machine setup, the alignment of the high speed spindle to the C-axis is also of high importance. A distinction between a decentration in X and a height error (Y) is difficult, because the error characteristics are the same. Special test structures are used to analyze the Y- and X-alignment errors independently to achieve a tool setting accuracy in the µm-range.
After a proper tool setting, the form deviation of an aspheric lens is in the range well below 200 nm (rms). A correction cycle consisting of a measurement step and a recalculation of the toolpath with respect to the occurring systematic errors leads to a increased form accuracy below 50 nm (rms). Interferometry or tactile profilometry are suitable techniques for measuring slightly aspherical lenslets. If the departure from the spherical shape is in the µm-range, lenslets are preferably to be measured with profilometers.

Figure 2 shows the figure correction steps for an aspheric sample lenslet. To verify the shape and the position of the lenslets, a tactile measurement strategy is chosen to enter the correction loop. The measurement machine used is an Ultra Accuracy 3-D Profilometer (UA3P-5) from Panasonic. This tactile measurement device, with a measurement range of 200 mm x 200 mm x 45 mm, uses a diamond stylus tool with a tip radius size of 2 µm to scan the surface. The accuracy over the measurement range is 100 nm in X,Y directions, with a repeatability of 50 nm. The probe measurement accuracy depends on the slope of the object. For slopes up to 30° the accuracy of the installed UA3P is assumed to be below 50 nm.
The measured profiles of the aspheric lenslet are leveled, averaged and filtered. The surface nodes from the original tool path are interpolated on the negative smoothed average for the figure correction. Reproducible systematic errors, that appear in every lens can be corrected by copying the corrected cutting data in the array.

4.3 Cutting Parameters for Diamond Milling

The selection of the cutting data for the milling process depends on the material and is a trade off between machining time and quality regarding shape and roughness. The diamond ball end mill shall be as large as possible to reduce the theoretical roughness and the cutting time. Feed and spindle speed are selected to generate a chip thickness of 1 µm to 3 µm. The separation distance between two successive turnings of the



(a) Form deviation of a lenslet before shape correction; form error 133 nm (rms).

(b) Form deviation of a lenslet after shape correction; form error 43 nm (rms).

Figure 3. Form error correction of lenslets in one milling correction cycle.

Archimedian spiral is 5 µm to 20 µm. Typical cutting parameters for micro milling of lenslets in an aluminum substrate are summarized in table 1.

Table 1. Cutting parameters for diamond micro-milling of lenslets

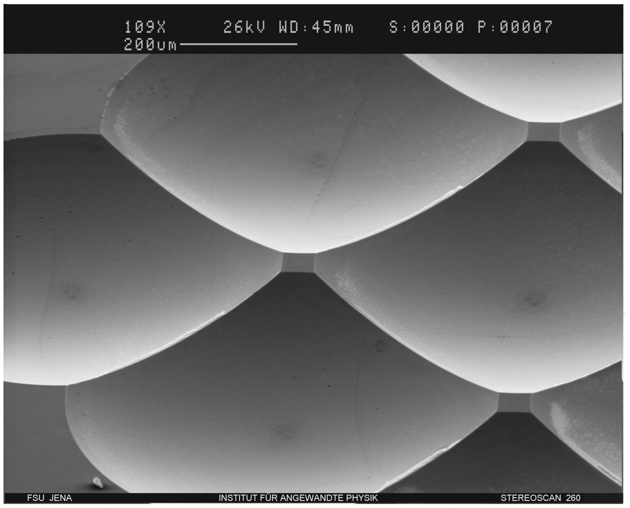
Cutting Data	
Diamond tool radius r_ε	0.8 mm
Depth of rough-cut $a_{p,rough}$	$<$ 100 µm
Depth of finish-cut $a_{p,finish}$	$<$ 10 µm
Spindle speed	$40,000$ rpm
Feed rate	40 mm/min
Feed per rev.	10 µm

The machining time for a single lenslet is in the minute range for the rough cut. The finish cut of a typical lenslet geometry takes 2 min to 5 min, depending on its size, the cutting tool radius and the feed. Machining times of more than 48 hour are typical for lens arrays containing a few hundret lenslets and more. Thus a very stable machine environment with an accurate temperature control is mandatory.

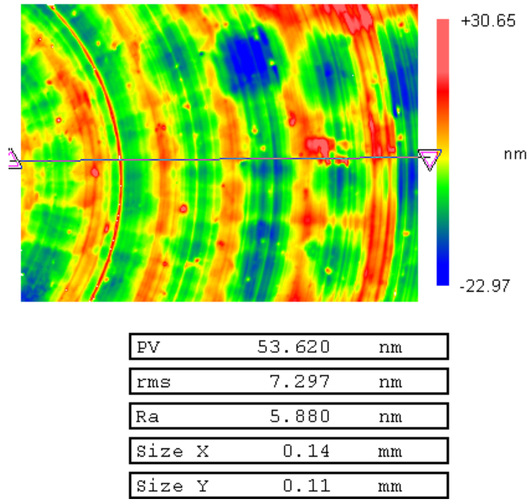
4.4 Results of the diamond micro-milling

The form error correction, which is conducted on one sample lens is used to generate the NC-code for the whole array. Eliminating all the systematic errors from the misalignment of the tool, the cutting edge waviness and the machine kinematics a figure error of less than $\frac{\lambda}{3}$ @ 633 nm can be achieved. Figure 3 shows the shape deviation of an aspheric lenslet with a sag hight of 137 µm, an aperture of 1 mm and an maximum edge slope of 30° before (a) and after form correction (b).

The surface finish strongly depends on the material used. In general the micro-roughness is comparable to the surface finish in diamond turning. In case of the brass micro lens array containing 1310 lenslets for wafer scale manufacturing, that is shown in figure 1(a) during the machining process, the achieved micro roughness is 7 nm (rms). The corresponding surface texture measured with white light interferometry is shown in figure 4(b). Still



(a) SEM image of overlapping diamond micro-milled lenslets



(b) Surface finish of a diamond micro-milled lenslet measured with white light interferometry

Figure 4. Surface quality of diamond micro-milled Lenses

visible is the theoretical roughness coming form the successive turnings of the Archimedian spiral of the tool on the surface. Furthermore high frequency concentric circles are noticeable, that might be the result of a slightly wear of the cutting edge or chips that are drawn over the optical surface. Figure 4(a) is an scanning electron microscopy (SEM) image of a very dense lens array with overlapping lenses. Visible are the sharp edges between two lenslets. The small µm-sized burr occurs only in one direction and can be removed by molding of the lenslets using a polymer.

The lens-to-lens registration accuracy is critical for a wide variety of applications such as wafer level manufacturing or coupling of light. The precision of lens-to-lens registration is inherent to the machine accuracy and the thermal stability of the environment. Typical values achieved are a position accuracy of ±5 µm over the entire substrate. A further enhancement can only be expected if the machines environment is controlled with an accuracy below 1 K and a temperature drift of less than 0.1 K/h.

5. ULTRA-PRECISION FREE-FORM TURNING

Ultra-precision turning machines are used to fabricate optics with a center of symmetry. Since 3D structures show no rotational symmetry, but rather high frequency asymmetric features, they are treated as be free-form geometries. The deviations from the rotationally symmetric reference features such as a sphere range from a few µm to mm or higher are manufactured on an ultra-precision lathe with additional strokes of the machining tool. The stroke of the diamond tool is synchronized to the angular position of the free-form surface in the machine's workpiece spindle. The forward and reverse motion is achieved either by the mechanical feed axis itself (Slow Tool Servo - STS), or an additional kinematic tool holder of low inertia (Fast Tool Servo - FTS). For high-frequency free-form geometries the FTS technology is generally preferred.
To show the potential of micro-optics manufacturing with the free-form manufacturing technique, we have chosen a micro-lens array design with a high frequency asymmetric portion. The lens array design shown in Figure 5 is a mold insert for an injection molding tool. The molded plastic lens array is used later as a 3D microoptical imaging element to transfer features from a 3D mask onto a curved substrate using lithographic process.[5] The mold insert contains 1,219 single spherical lenslets whose vertices are arranged on a spherical surface with a radius of 11 mm. The outer diameter of the array is 9.5 mm.
For the conducted studies of MLA manufacturing a Nanotech 450 UPL machine with an additional NFTS-6000, from Moore Nanotechnology Systems, LLC was used. The stroke of the FTS is ±3 mm. The integrated linear scale encoder with sub- nm resolution is in a closed control loop with a voice coil actuator, that positions the air bearing slide. With a maximum acceleration of 49.1 m/s^2, the NFTS is able to precisely follow an amplitude of 100 µm at 160 Hz.[6]

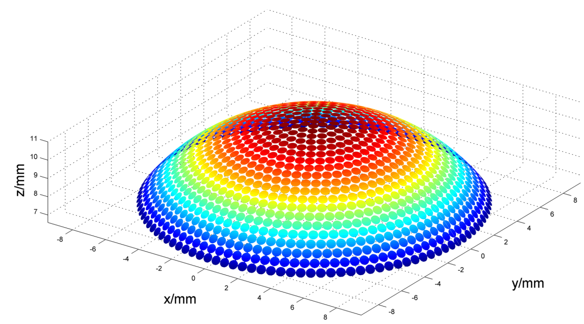
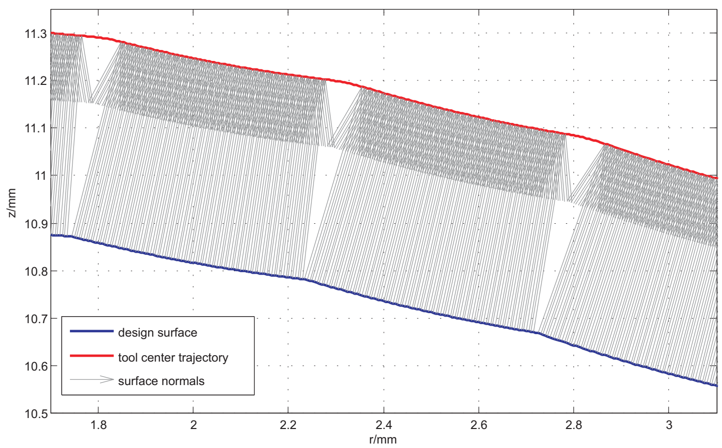


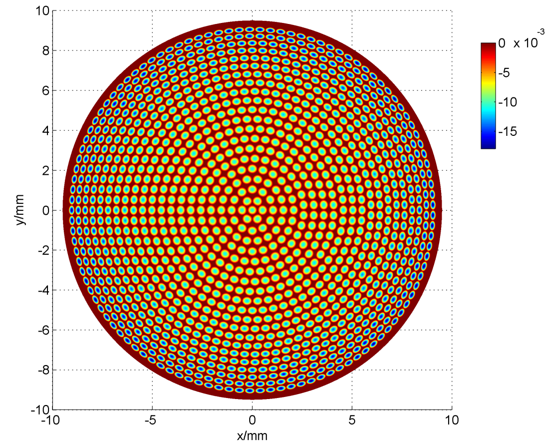
Figure 5. Geometry of the machined free form array containing 1,219 spherical lenslets on a hemisphere

5.1 Programming

The programming of the FTS can either be accomplished using commercial CAM-Tools such as NanoCAM 3D or proprietary software solutions. Although commercial software solutions are well developed for a wide variety of standard free-form machining applications, major drawbacks are the limited number of data points and possible approximation errors coming from the spline interpolation of high frequency free-form surfaces. The limitations of data points leads to an increased distance between the control points for the tool motion and consequently to a high shape deviation of high frequency free-forms. Typical spline interpolation errors are transitions between piecewise differentiable surfaces where spline-ringing may occur.
The representation of free-form data in the control of the FTS-System is a look up table of tool center points of the diamond tool in a polar coordinates. The streaming of data into this look up table allows the computing of large point cloud files containing some millions tool center nodes.
To transfer the 3D surface data with the high-frequency free-form features into a numerical code for machining, the piecewise differentiable surface is calculated in $25.2 \cdot 10^6$ supporting points in a polar mesh. Based on this point cloud, the tool radius correction is made to account for the cutting-edge geometry. Characteristic for any turning applications is the tool radius correction only in the radial direction. The cutting edge radius of the diamond tool tip in the angular direction is in the range of 10 Å − 20 Å can be neglected.



(a) Tool radius compensation of the diamond tool tip in the radial direction



(b) Asymmetric portion of the toolpath as input parameter for the look up table for the FTS control

Figure 6. Form error correction of lenslets in one milling correction cycle.

Figure 6 (a) shows the tool radius correction for one of the 12, 600 lines. Due to the discontinuities in the slope of the profile, the radius compensation is not defined in the transition area between the spheres. The missing points are calculated with a spline based interpolation. The resulting free-form portion of the tool center points are shown in figure 6 (b). Superimposed with the curved trajectory of the rotationally symmetric portion the geometric information for the production of this microoptical component is established.

5.2 Cutting Parameters for Free-form Machining

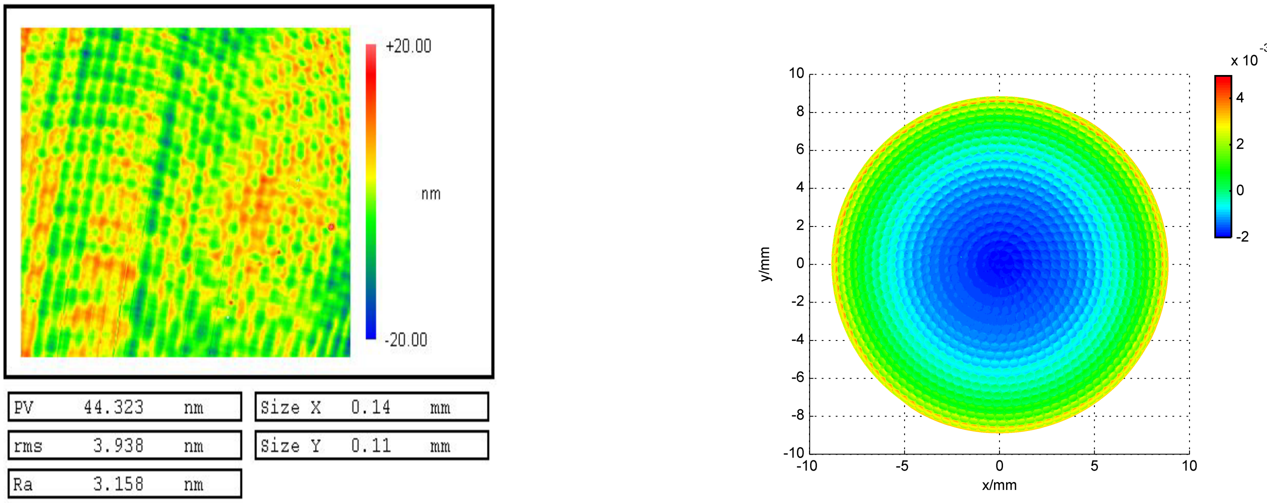
The total FTS-stroke needed to fabricate the lens array is 18 µm. According to the frequency response specification of the manufacturer, the FTS is able to operate at more than 200 Hz at this amplitude. Assuming a constant spindle speed, the highest necessary frequency of the FTS is expected on the outer diameter. Here 109 lenslets are machined on a common reference circle. The possible speed of 110 rpm is reduced to 25 rpm, because the excitation of 18 µm does not follow a sinusoidal motion. To achieve a reasonable smooth surface, the feed per revolution is adjusted to be in the micron range. The cutting data are summarized in table 2. The machining time for the whole array is 80 min. The material used is a high strength aluminum alloy as mold inserts for injection molding.

Table 2. Cutting parameter for the free-form machining of the lens array

Cutting Data	
Diamond tool radius r_ε	0.470 mm
Depth of rough-cut $a_{p,rough}$	$<$ 18 µm
Spindle speed	25 rpm
Feed rate	0.125 mm/min
Feed per rev.	5 µm

5.3 Results of the Free-Form Machining

The free-form micro lens array is machined in a two-tool process. The first diamond tool is used for rough cutting of the sphere and the reference surfaces, the second tool is mounted on the FTS and is used for the cutting of



(a) Micro roughness of the aluminum surface inside a lenslet is 4 nm (rms) measured with white light interferometry.

(b) Form deviation of the free-form machined micro lens array 1.37 µm (rms)

Figure 7. Quality in terms of shape and roughness of the free-form machined micro lens array on a curved surface.

the hemisphere with the spherical lenslets. After diamond servo turning, the micro lens array is cleaned and inspected.

5.3.1 Surface micro roughness

For characterizing the micro roughness, a Zygo White Light Interferometer NewView 600 with a 50x objective lens is used. To distinguish between form error and roughness profile a spherical surface with the design radius is subtracted from the surface data. The surface texture is shown in figure 7 (a). The finish of 4 nm (rms) is similar to ultra-precision diamond turning of aluminum alloys. The influence of the redundant kinematics of the FTS system is visible in the high frequent residuals in two direction.

5.3.2 Surface figure

The shape deviation of the complete free-form surface is measured with the tactile 3D-profilometer UA3P-5 from Panasonic. Since the piecewise differentiable surface topology is not programmable in the UA3P proprietary software, the profilometer is used to scan the surface only. The exported point cloud, representing the center points of the contact probe with a radius of 2.02 µm on the surface, is fitted and recalculated to obtain the shape error image as shown in figure 7 (b). The surface slopes for the radius correction of the diamond stylus are calculated using the design data of the free-form lens array.

The shape of this high frequency free-form surface deviates well below ± 1.5 µm (p-v) over a wide area from the design surface. Visible is a slight radius error of the overall sphere, whose origin is an inaccuracy of the radius value during the tool setting. An overshooting in the transition area between two lenslets, can not be discovered. The cutting speeds and feeds can be further increased to reduce the cutting time.

Figure 8. Free-form lens array mold insert containing 1,219 single spherical lenslets whose vertices are arranged on a hemisphere

6. CONCLUSION

Each of the introduced processes produced micro lens arrays in metal substrates to a level of quality that could be considered functional for replication for imaging or illumination optics. The diamond micro-milling process offers the opportunity to machine truly aspheric shapes and correct the residual shape errors to achieve form deviations down to 40 nm (rms) / 200 nm (p-v) required for imaging optics in the infrared to visible wavelengths. Also the micro roughness ranging around 7 nm (rms) complies to these spectral ranges. For shorter wavelengths, the micro roughness has to be improved to reduce scattering losses of the optical surface.
The design freedom regarding possible shapes of the lenslets is very high. Edge slopes up to 60°and more are feasible and a high fill factor with intersecting lenslets is possible. A drawback and cost driver is the increased production time of diamond micro-milled lens arrays. Besides the time for the tool setting, the cutting time of an array containing thousand lenslets and more can be up to several days continuous machining.
Nevertheless, the ability to manufacture deep lenslets with sag-heights up to several hundred µm with truly aspheric shapes on arbitrary positions on large substrates offers an additional degree of freedom for the design of micro lens arrays, either directly structured or as master for replication. These achievements show the potential application of this technology for fabricating micro imaging systems on the wafer level for cellular phones or sensor devices.

Free-form machining using a FTS is more demanding regarding the tool path programming, but shorter machining times can be expected. The FTS used is expedient for machining high frequency free-form surfaces with a size smaller than ∅ 50 mm. The reason for this drawback is the amount of data necessary to describe the array in the look up table. An uniform polar meshing with a sufficiently dense point spacing of less than 10 µm raises the computing and loading times significantly.
The processing time of only 80 minutes for the machining of the described high strength Aluminum alloy injection-mold insert and the surface quality of 4 nm (rms) show the good applicability of the free-form machining process for structuring of these small free-form optics. The shape deviation in the µm-range could be considered functional for infrared imaging optics and for a broad spectrum of illumination optics. Correction cycles to improve the shape of the optical element after a metrology step are not targeted for high frequency free-form surfaces, because contributions to the shape irregularities are caused by the inertia of the FTS system and inconsistent cutting conditions over the diameter of the workpiece.
Feasible geometries are mainly limited by the diamond cutting tool geometry with a clearance angle up to 40° and the radius of the diamond tool used. Replication by injection molding opens up the possibility to efficiently and economically reproduce these geometries. The free-form machining can realize its full potential as an adequate addition to lithography for structuring three-dimensional optics in the mesoscopic scale.

ACKNOWLEDGMENTS

The authors acknowledge the financial support by the Fraunhofer Society that enabled the collaboration between the Fraunhofer Institute for Applied Optics and Precision Engineering (IOF) and the Ohio State University, Industrial and Systems Engineering in the Fraunhofer program Prof X^2.
This material is partially supported by the InnoProfile project Nanoreplika, Grant No. 03IP609, funded by the Federal Ministry of Education and Research (BMBF) of Germany.
This material is partially based on work supported by National Science Foundation under Grant No. CMMI-0928521. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

[1] Popovic, Z. D., Sprague, R. A., and Connell, G. A. N., "Technique for monolithic fabrication of microlens arrays," *Appl. Opt.* **27**, 1281–1284 (Apr 1988).

[2] Radtke, D. and Zeitner, U. D., "Laser-lithography on non-planar surfaces," *Opt. Express* **15**, 1167–1174 (Feb 2007).

[3] Scheiding, S., Steinkopf, R., Kolbmüller, A., Risse, S., Eberhardt, R., and Tünnermann, A., "Lens array manufacturing using a driven diamond tool on an ultra precision lathe," *9th International Conference of the European Society for Precision Engineering and Nanotechnology EUSPEN - San Sebastian, Spain, 2009* **Vol. II**, 423–426 (2009).

[4] Davis, G. E., Roblee, J. W., and Hedges, A. R., "Comparison of freeform manufacturing techniques in the production of monolithic lens arrays," *Optical Manufacturing and Testing VIII* **7426**(1), 742605, SPIE (2009).

[5] Li, L. and Yi, A. Y., "Microfabrication on a curved surface using 3d microlens array projection," *Journal of Micromechanics and Microengineering* **19**(10), 105010 (2009).

[6] Moore Nanotechnology Systems, LLC, "NFTS-6000 Specification Overview." Product Brochure (Jan 2007). sales@nanotechsys.com.