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Fabrication of plastic microlens array for array microscopy by three-dimensional diamond micromilling

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Abstract

Two lens arrays of 20 lenses (4×5) are fabricated in polystyrene (Rexolite 1422) using a 3-D, three-axis micromilling process. The lenses of one array are concave ($R_{\text{curv}} = -2$ mm) and the lenses of the other array are convex ($R_{\text{curv}} = 2$ mm). A method for correcting a 3-D micromilling program for a single lens is described and evaluated. The lens separation is 4 mm and $\varnothing_{\text{diam}} = 2.6$ mm for all lenses. Based on a measurement of key optical parameters (radius error, wavefront error, and surface roughness), micromilled lenses are shown to be of high optical quality compared with the form error and surface roughness obtained with plastic injection molded lenses.

Keywords

array microscopy; lens array; diamond milling; micro-milling

1 Introduction

Microscope arrays are arrays of miniature high power objectives, each of a similar size to a miniature endoscope¹ capable of imaging biological specimens, such as histology slides, sputum smears, or cell cultures. Such arrays have already been put to use in the field of pathology,² but have not yet become widespread in clinical use or in biomedical research. There is still great potential for array microscopes in biology, but the high cost of developing these devices remains a hurdle. Techniques currently used to make lens arrays include UV lithography, thermal reflow, compression molding, microforging, diamond machining, and often combinations of multiple techniques.^{3–8} These technologies have provided the ability to fabricate lens arrays designed for a wide variety of uses, but not all of these techniques are capable of producing the size lenses needed for an array microscope at the quality needed for at least a prototype system. Diamond machining technology is among the best at producing surfaces with the sag, radius, and diameter needed of miniature microscope lenses. This technology is often used to fabricate a master that can then be used in a replication process, such as plastic injection molding.⁹ 3-D diamond milling, or micromilling, has been shown effective in producing these masters in metal.¹⁰ Using a lens array mold to produce a finished product of state of the art optical quality is not trivial, however. Obtaining a single finished prototype from a mold can be difficult and therefore expensive. Molding may only be economical in the case of microscope arrays at the commercial production phase, not at the development phase, unless the researchers have both mold-making and molding equipment at their disposal. For many research and development laboratories, especially academic laboratories, such a complete facility can be

prohibitively expensive, as would be the cost of outsourcing the production of a single prototype by molding. The ability to produce a finished part on one machine in one step brings this cost of development down significantly.

Lens arrays have been produced in this single-step fashion in poly(methyl methacrylate) (PMMA) using a plunge milling method, but the method of fabrication error correction is etching of the tool, and it is only good for lenses with a diameter of 1 mm or less.⁸ Diamond micromilling, since it is capable of producing state of the art lens molds, is a logical choice for direct fabrication. It is therefore the goal of this study to show the capability of 3-D diamond milling to produce high power lens arrays directly in plastic with state of the art form accuracy and optical quality surface roughness. Both types of lens shapes, concave and convex, are shown to fully demonstrate the ability of this process to produce all of the lenses needed in any array microscope design.

2 Methods

2.1 Equipment and Setup

The machine used is a four-axis (X, Y, Z, and C) Nanotech 250 Ultra-Precision Lathe (UPL) (Moore Nanotechnology Systems, Swanzey, New Hampshire). The C axis control is not used, so there are three automated axes. The equipment used is shown in Fig. 1. The milling tool used is a 0.529-mm radius ball nose endmill made by Contour Tool (Elyria, Ohio). The Moore Nanotechnology diamond turning software suite was also used, including NanoCAM 1.0, NanoCAM 2D, Work Spindle Trim Balancer, and Wavefront Error Correction (WEC) software. A spindle adapter is fixed onto the face of the work spindle, and a Swiss Rego-Fix (Indianapolis, Indiana) ultraprecision collet and collet nut hold the endmill in place. The Nanotech 250 comes with an internal spindle balancer that is capable of accurately balancing the spindle at the relatively low spindle speeds used in this study. An external spindle balancer was therefore unnecessary. The endmill must be aligned with the spindle axis as best as possible, as described in Ref. 10. Misalignment can lead to form errors across the entire part, and a microscopic nub-like feature at the lens center. The tool is assumed to be centered with respect to the tool shank, and the position of the spindle adapter is adjusted while loosened until the runout of the tool shank is less than 1.5 μm . The electronic gage head shown in Fig. 1 (Mahr Federal Incorporated, Providence, Rhode Island, model EHE-2056) was used to measure the runout of the tool shank. Due to the tightness of fit between the spindle adapter and work spindle, no further adjustments could be made to the tool position once the spindle adapter was secured. The gage head was also used to measure the tilt of the work piece. The compound goniometer system is used to correct this alignment. The part tilt can be reduced to 2 arc min or less with respect to the spindle axis using this method. A linear variable differential transformer (LVDT), used to measure 2-D lens profiles, is calibrated before the spindle adapter is mounted. The LVDT was calibrated by measuring a one inch calibration sphere and storing the measured error. This reference file measurement was then used to adjust later measurements of micromilled lenses.

2.2 Cutting Programs

A lens is micromilled using a spiral cutting program,¹⁰ as shown in Fig. 2. The angular feed rate of the tool is nearly constant, so the linear feed rate varies from the edge of the lens to the center of the lens. The micromilling parameters used in this study are shown in Table 1. A separate rough cut program was created to remove the bulk of the material for both lens types. A semirough cut was not done. The part programs were generated using NanoCAM 1.0. This software compensates for the shape of the spinning tool with the assumption that the solid rotation of the endmill is spherical. Waviness or misalignment of the tool makes this shape nonspherical and results in form errors, which must be corrected. Since the lenses

being made in this study are rotationally symmetric, the same techniques used to correct tool path errors in single point diamond turning can be used to correct a 3-D micromilling tool path. The Nanotech WEC software is capable of obtaining a 2-D error profile from a 2-D contact profile measurement of the part and a reference measurement of a calibration sphere. NanoCAM 2-D can be used to generate a corrected 2-D sag table, which can be converted into a corrected 3-D sag table and corresponding tool path by NanoCAM 1.0. The results of a single tool path correction applied to a micromilled lens is shown in Fig. 3.

3 Results

Two lens arrays were fabricated in this study using the programs generated for convex and concave lenses. The arrays are shown in Fig. 4. Measurements were taken of each lens radius, wavefront error, and roughness. Radius and wavefront error were measured using a Zygo (Middlefield, Connecticut) PTI250 Fizeau interferometer with an f/1.5, 25-mm-diam, 655-nm wavelength transmission sphere. The radius measured is the distance between the cat's eye and confocal positions. Spatial modulations with wavelengths shorter than $15\text{ }\mu\text{m}$ were removed. Surface profiles of the lenses were measured using a Zygo New View 5032 Optical Profiler. These measurements were taken over a $0.27 \times 0.35\text{-mm}$ field of view at a lateral resolution of $0.56\text{ }\mu\text{m}$. Roughness estimates were calculated using these surface profiles. Modulations in the surface profile of wavelengths longer than $26.7\text{ }\mu\text{m}$ are attributed to form error and removed. The type of filter used is a Gauss spline filter. An interferogram from the PTI250 and a surface profile measurement from the new view are shown in Fig. 5.

The tolerances typically achieved for single plastic injection molded lenses are compared to the errors measured in this study in Table 2. The quality surface finish of the lenses in the arrays made in this study was on average higher than what can be obtained using low-cost plastic injection molding processes. Still, with an $R_q \approx 12$ to 15 nm , these lenses are of optical quality. The wavefront errors of these lenses are all very good, although in this category the highest quality lenses made by plastic injection molded lenses can still outperform these lenses. Few if any plastic injection molding processes can provide a tighter tolerance on radius error. Most notable is that every lens measured has less than 0.3% radius error (Fig. 6), which is classified as the tightest of tolerances for plastic injection molded lenses.¹¹ One of the concave lenses was scratched at the apex, so its cat's eye position could not be found, and therefore its radius could not be measured.

4 Conclusions

This study shows the ability to correct a 3-D micromilling tool path for a rotationally symmetric surface using traditional 2-D tool path correction techniques, and then to fabricate an array of those lenses with excellent repeatability, directly in plastic and without the need for additional equipment to replicate a mold. The lenses made using this technique are of excellent optical quality and are suitable for building high NA, high power microscope objectives with state of the art tolerances on lens radius and form. Future work will include cutting lenses on both sides of a work piece, with precise alignment of the surfaces on both sides, and eventually a complete array microscope with color correction.

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Biography

Brian McCall received his BS degree in computer engineering at the University of Oklahoma in 2003. He is currently pursuing a doctoral degree in bioengineering at Rice University, Houston, Texas, in the laboratory of Tomasz Tkaczyk. His research interests include microscopy, optical design and fabrication, and biomedical imaging.

Tomasz S. Tkaczyk is an assistant professor of bioengineering and electrical and computer engineering at Rice University, Houston, Texas, where he develops modern optical instrumentation for biological and medical applications. His primary research is in microscopy, including endomicroscopy, cost-effective high-performance optics for diagnostics, and multidimensional imaging (snapshot hyperspectral microscopy and spectropolarimetry). He received his MS and PhD degrees from the Institute of Micromechanics and Photonics, department of Mechatronics, Warsaw University of Technology, Poland. Beginning in 2003, after his postdoctoral training, he worked as a research professor at the College of Optical Sciences, University of Arizona. He joined Rice University in the summer of 2007.

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Fig. 1. Nanotech 250 UPL setup for micromilling. Inset: LVDT unmounted without covering.

Fig. 2.
Example tool path generated by NanoCAM 1.0 for a rough-cut micromilled convex lens having a 0.2-mm/rev radial feed rate.

(a)

(b)

Fig. 3. Nanotech WEC measurement of lenses cut with (a) an uncorrected program and (b) a program with one correction iteration.

Fig. 4.
A 4×5 array of concave lenses (left) and a 4×5 array of convex lenses (right), both made by micromilling.

(a)

(b)

Fig. 5.
(a) Fizeau interferogram of convex lens and (b) surface profile of same lens obtained from a white light optical profiler.

Fig. 6. Radius error of lens arrays. Lens 1 of the concave array sustained a scratch at the apex of the lens, preventing measurement of its radius using the Zygo PTI250.

Table 1

Single lens micromilling parameters.

	Convex	Concave
Part radius (mm)	2.0	−2.0
Clear aperture diameter (mm)	2.6	2.6
Point density (pts/deg)	1	1
Spindle speed (RPM)	3400	3400
Radial feed rate ($\mu\text{m}/\text{rev}$)	2.5	5.0
Angular feed rate (deg/s)	125	125
Linear feed rate at part edge (mm/min)	215	126
Linear feed rate at part center (mm/min)	0.105	0.143
Depth of final cut (μm)	15	15

Table 2

Tolerances of optical parameters ($\pm$ standard deviation) of convex and concave arrays micromilled in this study. State of the art tolerance of single plastic injection molded lenses (not arrays of lenses) is 0.3%, tight tolerance of PV wavefront error of plastic injection molded lenses is 150nm, etc.¹¹ R_q refers to the rms surface profile after filtering.

	Convex	Concave	Versus injection molding
Radius error (%)	0.102 $\pm$ 0.054	0.180 $\pm$ 0.034	0.3 State of the art
PV wavefront error (nm)	175 $\pm$ 33	179 $\pm$ 43	150 Tight
RMS wavefront error (nm)	31.4 $\pm$ 7	23.6 $\pm$ 5	30 Tight
R_q (nm)	12.825 $\pm$ 2.45	15.813 $\pm$ 4.19	10 Low cost