Optifab 2007, SPIE Symposiuum on Optical Fabrication, 14-17 May 2007, Rochester Riverside Convention Center in Rochester, New York USA.

Microforging technique for rapid, low-cost fabrication of lens array molds

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ABSTRACT

Interest in micro-optical components for applications ranging from telecommunications to life sciences has driven the need for accessible, low-cost fabrication techniques. Most micro-lens fabrication processes are unsuitable for applications requiring 100% fill factor, diameters around 1 mm, and scalability to large areas with millions of lenses. We report on a flexible, low-cost mold fabrication technique that utilizes a combination of milling and microforging. The technique involves first performing a rough cut with a ball-end mill. Final shape and sag height are then achieved by pressing a sphere of equal diameter into the milled divot. Using this process, we have fabricated molds for rectangular arrays of 1-10,000 lenses with apertures of 0.25-1.6 mm, sag heights of 3-130 μm, inter-lens spacings of 0.25-2 mm, and fill factors of 0-100%. Mold profiles have roughness and figure error of 68 nm and 354 nm, respectively, for 100% fill factor, 1 mm aperture lenses. The required forging force was modeled as a modified open-die forging process and experimentally verified to increase nearly linearly with surface area. The process is easily adapted to lenticular arrays. Limitations include milling machine range and accuracy.

Keywords: Microforging, lens array, micro-optical, injection molding, lenslet, ball end micro-milling, microlens

1. INTRODUCTION

Miniaturization of devices and techniques to sub-millimeter scales holds much promise, including reducing cost, increasing portability and speed of analysis, and parallelism. Optical engineering must match these device sizes to continue to deliver, for example, sensitive, non-invasive, accurate measurement. Some instrumentation[1] requires arrays of thousands of tiny high numerical aperture (NA) lenses, tightly packed with 100% fill factor (the ratio of the active refracting area to the total contiguous area occupied by the lens array, f_f), with apertures of 1 mm and f/#<5.

Current micro-lens array mold master manufacturing techniques include photoresist reflow,[2,3] laser beam shaping of photoresist[4] or glass,[5] photothermal expansion,[6] ion exchange,[7] diamond turning, and micro-droplet printing.[8] Save diamond turning, these processes can often deliver exquisite replication of 15-500 μm aperture lenses that are often limited to square close-packed (f_f=π/4=78%) or approaching hexagonally close-packed (f_f=91%). Efforts to increase f_f have not resulted in accurate lenses over the full aperture.[9] Achieving high NA can also be challenging, as typical lens' sags of this size are 1-20 μm. These processes can also be relatively expensive and time consuming to implement, and are limited in area that can be patterned to ∼100 millimeters.

Diamond turning, for high machine and tooling costs, can produce microlens arrays with 250 nm figure error and 9 μm roughness over 1 mm apertures, as well as a variety of other sizes. High costs can be distributed if the master is replicated, such as by injection molding. Limitations include the area that can be patterned, high start up costs, and fragile tooling. Sag height can be limiting as well, as the tools would need to match the part slope over large distances (e.g., several millimeters). In this work, we sought to develop a low cost, flexible mold fabrication technique that could match the figure error of diamond turning.

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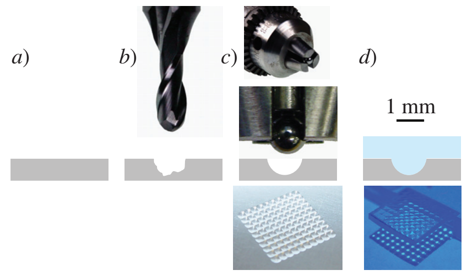

Figure 1. Schematic of lens array mold manufacturing process and photographs of a 100 lens array mold and molded part. *a*) A blank aluminum mold is faced and polished. *b*) A rotating ball-end mill is used to cut an array of divots. *c*) A tungsten-carbide sphere is lowered onto the surface to deform the divots to the final shape. *d*) The mold is used to injection mold lens arrays, as we have done for arrays containing over 10,000 lenses.

2. METHODS

Our milling and micro-forging process is shown schematically in Fig. 1, accompanied by photographs of a 100 lens mold and injection-molded lens array. To fabricate the lens array molds, we first face and polish an aluminum substrate. Next, we perform a rough cut with a ball-end mill. The final shape and sag height are then achieved by pressing a sphere of equal diameter into the milled divot. The reasoning behind the process is that the mill determines the majority of the mold figure, and subsequent forging with a ground, polished sphere (206 nm figure error, 19 nm roughness) imparts a near perfect figure and roughness to the mold without substantial deformation that could affect neighboring lenses in a tightly-packed array. After mold fabrication, injection molding is performed. In practice, molds were created using titanium-nitride coated ball-end mills and tungsten-carbide spheres. Using this process, we have fabricated molds for rectangular arrays of 1-10,000 spherical lenses with apertures of 0.25-1.6 mm, sag heights of 3-130 μm, inter-lens spacings of 0.25-2 mm, and f_f of 0-100%.

A machining center (Haas, VF-OE) was used for lens mold fabrication. The system has 5.0 μm accuracy and 2.5 μm repeatability in all axes with work volume of $0.8 \times 0.4 \times 0.5$ m^3. Experiments to determine required forging force were performed on a 90 kN hydraulic press (Devin, LP-500).

The quality of the lens molds produced with this technique was determined using two parameters: figure error and average roughness (Ra). These two parameters were calculated from mold surface profiles measured using a stylus profilometer (Mitutoyo, SV-3000) with a 2 μm radius tip, 1 μm lateral resolution, and 1 nm transverse resolution. From this raw data, we implemented several algorithms to measure figure error and surface roughness. Figure error was calculated over 80% aperture by comparing the measured surface profile to the desired shape. By shifting the desired shape relative to the measured profile, we find the optimal fit (least error) and compute their average absolute difference. For roughness, we first remove from the measurement low frequency information associated with the mold's round shape by successively fitting and subtracting 2$^{\text{nd}}$, 1$^{\text{st}}$, and 0$^{\text{th}}$ order polynomials to measurement segments. The roughness is then calculated as the average Ra of the series of sections.

3. THEORY

As we seek to create spherical lens impressions in an aluminum mold, theoretical modeling of the required force was performed. We modified the open-die forging model by Kalpakjian[10] to derive a new model for hemispherical impressions on a planar substrate, assuming that the tool is much more stiff than the workpiece, as

$$F = Y_f \pi A_s \left(1 + \frac{\mu d}{3z}\right), \tag{1}$$

where F is the forging force, Y_f is the flow stress of the material ($\approx$ true stress at 100% true strain), A_s is the impression surface area, μ is the coefficient of friction ($\approx$0.2), d is the lens aperture, and z is the forge depth.

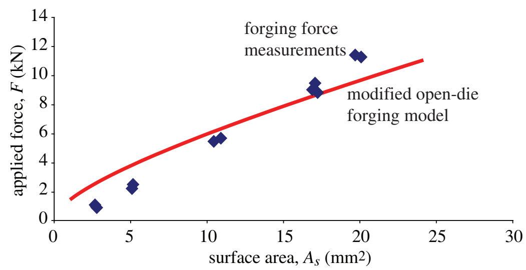

Figure 2. Forging force theory and experimental measurements vs. molded surface area.

A_s and z are given respectively by

$$z(d, R) = R - \sqrt{R^2 - \frac{d}{2}^2}, \tag{2}$$

and

$$A_s(d, R) = 2\pi R^2 \left(1 - \frac{\sqrt{R^2 - \frac{d}{2}^2}}{R}\right), \tag{3}$$

where R is the lens radius of curvature. This model should predict the required force, F, to create a spherical impression of depth, z, and diameter, d, for a range of mold materials, lens sizes and sag heights.

4. RESULTS AND DISCUSSION

Using a hydraulic press to form impressions in an aluminum 6061 substrate, we were able to compare our model with experiment, as shown in Fig. 2. These experiments were conducted with several sphere diameters (10-25.4 mm). The results indicate that one can well predict the required forging force for typical lens sizes. For the smallest surfaces areas, the conservative model deviates the experimental results by up to three times. Typical lenses with 1.41 mm aperture, 2.5 mm radius of curvature, have surface area of 1.6 mm^2 and require 1 kN of forging force. Our machining center (Haas VF-OE), used for this work, has 25 kN forging force capability.

Numerous molds were fabricated, measured, and analyzed as described. The results for the mold figure error and roughness are shown in Fig. 3. For lens arrays with $f_f \geq 80\%$, figure error decreases monotonically with increasing mill depth (decreasing forge depth). Since the forging process does not remove material, but plastically deforms it, the neighboring lenses in tightly packed arrays are affected by the forging process. On the other hand, the roughness generally increases with increased mill depth. This can be attributed to the milling tool's roughness, which is much larger than the sphere's 19 nm roughness.

The advantage of the combined process is clear when comparing the figure error and roughness of the lens mold to that created by either process alone. Purely milled divots typically have 1.7 μm figure error and 300 nm roughness, independently of f_f. Purely forged divots have figure error that is dependent on f_f (See Fig. 3 *left*), at worse 1.8 μm for 100% f_f, and roughness of 31 nm independent of f_f. The optimal combination results in a figure error that is 4-5× better than either process alone, while roughness remains good at ∼68 nm.

For 100% f_f molds made using the optimum combination of milling and forging, measurements of injection-molded lens arrays showed that figure error increased from 354 nm to 939 nm while roughness decreased from 68 nm to 36 nm. This is reasonable given the 1-2% linear shrinkage of polymethyl-methacrylate (PMMA) upon cooling after molding, and corresponding attenuation of high frequency features.

We also fabricated 100% f_f lens array molds with 0.25-1 mm apertures and constant radius of curvature of 2.5 mm. Roughness was independent of lens aperture, averaging 75 nm. Figure error improved as lens aperture was reduced: 1 mm diameter, 50.5 μm sag lenses had 0.35 μm figure error (See Fig. 3 *left*) , 0.5 mm diameter, 12.5 μm sag lenses had 0.15 μm figure error, and 0.25 mm diameter, 3.1 μm sag lenses had 0.11 μm figure error. Smaller apertures are prohibited by the accuracy of the machining center and end mill tool.

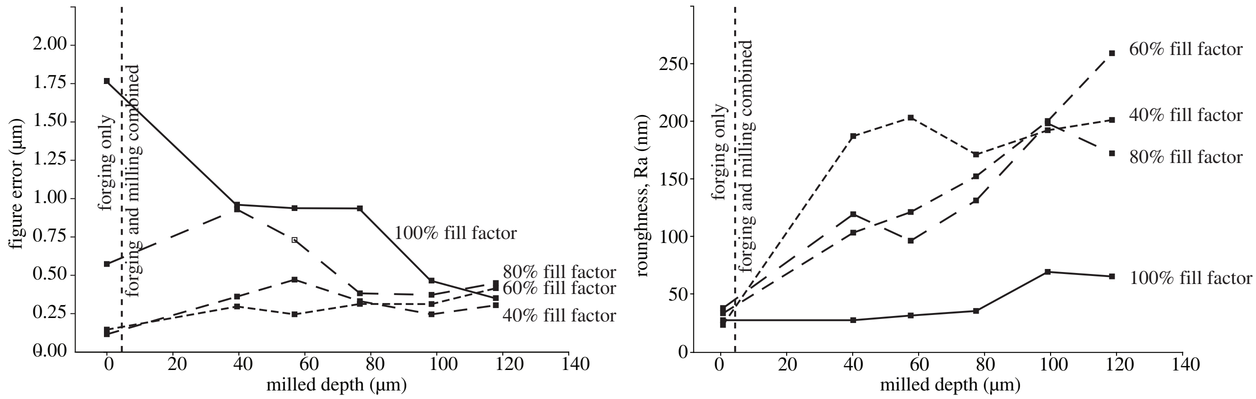

Figure 3. Figure error (*left*) and roughness (*right*) of lens array molds. All lenses have 120 μm total sag height, so increasing milled depth implies that a larger percentage of the final figure was determined by milling. (*left*) As milled depth increases, the figure error generally improves. The effect is most pronounced for fill factors $\geq$80%. (*right*) As milled depth increases, the roughness increases (degrades) somewhat to a plateau, but is still small. For fill factors less than 80% forging alone has a superior combination of figure error and roughness. For 100% fill factor lens arrays, milling to the full depth and subsequently forging to the full depth results in the best figure with reasonable roughness.

Drawbacks include required calibration of the depth of milling and forging tools, which has an inherent uncertainty of 1 μm. Thermal expansion of the machining center can affect lens sag. In addition, elastic "springback," upon unloading the forge can contribute to sag errors. All combined, we measured these factors to affect sag by, at most, 20 μm. Lenses with large surface areas (e.g., >14,000 mm^2 each), may exceed typical machining center force capabilities.

5. CONCLUSIONS

For lens arrays with $f_f \geq$80%, the combination of milling and microforging offers great potential for the fabrication of molds with low figure error and roughness. For such tighly-packed lens arrays varying in lens aperture from 0.25-1 mm, we have demonstrated that figure error will be $\leq$354 nm and roughness will be $\sim$75 nm. We have used this process to mold lens arrays containing more than 10,000 lens elements, over a 102$\times$104 mm^2 area. Should lens arrays with <80% f_f be desired, forging alone can provided figure errors of <250 nm and roughness of 31 nm. Thus, this flexible, low-cost, scalable process could supplant many other lens array manufacturing processes that operate within this size and density range.

ACKNOWLEDGMENTS

We gratefully acknowledge the generous support of the National Science Foundation, Sandia National Laboratories, the MIT BioInstrumentation Laboratory and the MIT Undergraduate Research Opportunities Program.

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