Fabrication Examples of Non-rotationally Symmetric Optical Elements

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Abstract

Two examples of a fabrication of non-rotationally symmetric optical elements are presented here, with a particular attention given to the techniques chosen for the process. Abrasive Grinding is mentioned briefly as the technique which originated many of the early applications of non-symmetric optics, followed by Fast Tool Servo turning and Diamond Milling. Metrology tools for non-symmetric optics, or lack thereof, is mentioned. The examples chosen represent the application of Fast Tool Servo to the fabrication of typically smaller optical elements which are used in computational imaging systems (Wavefront Coding), and Diamond Milling applied to the fabrication of larger optics found in rear-screen projection systems.

Introduction

Early examples of free-form optics in consumer products are found in Polaroid cameras, and were well described on many occasions (see, for example, [1] and references cited therein). The earliest free-form lens is found in a viewfinder of a later model SX-70 camera, which was introduced in 1973. The lens was mass-produced by injection molding; the optical surface in the mold cavity was fabricated by abrasive grinding of steel with a commercial 3-axes milling machine adapted to work beyond its originally intended accuracy. The machined surface was quite rough and required extensive post-polishing in order to bring it to what was considered "optical quality". At that time semi-automated and in some cases hand polishing was quite common and required an extensive set of skills and sometime an artful approach. The fabrication process followed the "machining – profilometry – polishing – profilometry – compensation" iterative cycle with very good results. It is worth mentioning that profilometry played a central role in this process, with its accuracy exceeding that of machining by nearly two orders of magnitude. In 1994 a new 3-axes ultra-precision machine was completed, specifically designed to improve the profile accuracy and surface finish of abrasively ground tooling for free-form optics. The resulting profile accuracy showed an order of magnitude improvement, and the achieved surface roughness (10-15nm RMS) virtually eliminated iteration steps due to the polishing process. The abrasive grinding process produced very durable tools for injection molding, many of them producing tens of millions of lenses. The process is however very time consuming and requires special considerations, such as flood cooling and tool wear, which makes it rather unsuitable for low volume fabrication purposes. Nevertheless it was used, as the only process available, to fabricate tooling for some of the early examples of phase masks for wavefront coding, and in some cases even single free-form shapes, for example in glass or germanium.

Over the years new fabrication techniques evolved, such as Fast Tool Servo, Diamond Milling, Slow Tool (or Slide) Servo. Recently new exciting results were announced by Tohme and Lowe of Moore Nanotechnology Systems [2], on the application of Slow Slide Servo technique to the fabrication of Freeform Optics; these results are particularly encouraging because they are coming from machine-tool industry, which stimulates broader use of these tools where applicable.

The fabrication examples we are describing below are based on techniques which we use routinely to fabricate freeform optics. They are Fast Tool Servo and Diamond Milling.

Fast Tool Servo

The need for a fabrication process of freeform optical elements, which would be responsive enough to satisfy the demands of rapidly changing designs and applications, directed our attention towards a process known as Fast Tool Servo (FTS) – higher bandwidth (e.g. piezo-actuated) secondary stage carrying the cutting tool in a diamond-turning operation. Our approach was driven by a specific application, so we have defined the performance parameters of the FTS accordingly, and then designed and build a unit satisfying them. Our demands were as follows:

- Modularity: the actuator unit should add no more mounting complexity then changing a tool-post.
- Simplicity of controller interface: no external controllers; utilize existing machine controller resources without hardware modifications.
- Ease of programming: machine controller commands preferable, with some numerical pre-processing.
- High structural stiffness; 100-200Hz bandwidth; 150-200µ amplitude displacement.

Our implementation of a FTS is based on a flexure carrying the cutting tool, very stiff in the non-actuated directions; the flexure is displaced by a 180µ piezo-actuator linearized for histeresis by the driving electronics. The position of the actuator is controlled in an open-loop fashion by the machine controller. A capacitive gage, permanently mounted in the flexure assembly, is used to calibrate and verify the position. We were utilizing the existing encoder in the machine spindle to resolve its phase, with satisfactory results for the types of parts we were machining. Recently, however, we have added high-resolution encoders on machines where we thought it might be advantageous.

The open-loop bandwidth of our FTS actuator is 150Hz, which is sufficient for most of our applications (we are generally cutting at 600-1500RPM). We analyze each surface fabricated to determine its local curvature and spatial frequency content. We compensate the tool path for tool shape and, when needed, for frequency response of the actuator.

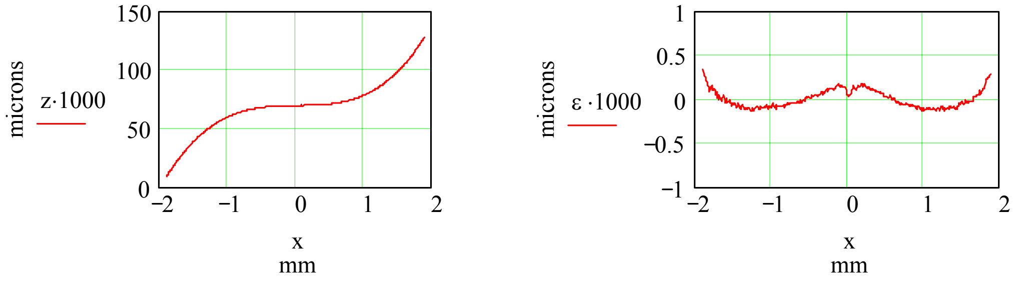
Diamond Milling

Diamond Milling (or Diamond Flycutting) is a process of sculpting a free-form surface with a rotating diamond tool (e.g flycutter) on a three-axes machine. Many aspects of Diamond Milling (DM) resemble abrasive grinding: the tool path is routinely rasterized and compensated for a three-dimensional shape of the tool (in most cases a toroid); the process is rather time consuming due to a limited cutting action of the tool as a fraction of its rotation. Advantages are many: no flood cooling is necessary because if its non-abrasive nature; tool wear is practically nonexistent; surface finish is “tunable” to same extent and can be calculated from the tool geometry and machining parameters (surface finish is generally traded for machining time); surface form and spatial orientation are well determined; surface size and sag bound only by axes travel limits. We use Diamond Milling routinely on all materials which are diamond-turnable (e.g. most of plastics, non-ferrous metals and alloys). Larger radius cutting tools are preferred in this process (limited only by the local surface curvature), so tool path compensation is important. Today, some CAM applications offer limited help with that. In addition, we have independently developed software tools to generate tool paths for an arbitrary spatial orientation of a parameterized toroidal cutting tool with respect to a free-form surface.

Fabrication of Free-Form Optical Elements for computational imaging systems

Recent developments in computational imaging systems [3], and the introduction of the concept of Wavefront Coding [4] in particular, created a need for a fabrication process of freeform optical elements with very specific geometry; a typical wavefront coding optical element (WCOE), although varies in size (diameter) depending on the application, is a plano-freeform lens with PV sag variation ranging from a few microns to 160µ in the most extreme cases we have encountered. The free-form functional description may be a simple cubic of the form $z(x,y)=a(x^3+ y^3)$ (which often is referred to as a cubic phase mask (CPM)), or a more complex function of a general form $z(r,\phi)=P(r)\cdot M(\phi)$, where $P(r)$ is a radial power polynomial, and $M(\phi)$ is azimuthal modulation.

The initial attempts to fabricate WCOE were by free-form abrasive grinding of steel for injection mold tooling [5]. It became clear, however, that FTS may be ideally suited for this type of a surface and efforts were made to develop it according to the guidelines described in the Introduction. Since the free-form surface is diamond-turned with FTS, the fabrication time is reduced to a typical turning time; this is suitable for low volume fabrication (1-10 parts) but still may be prohibitively expensive for larger volume (100+ parts). For the larger volume we choose injection molding, turning the tooling with FTS either in aluminum (soft-tool for quantities of 100’s) or nickel alloy (hard-tool, for larger quantities).



CPM1 Measured profile

CPM1 Profile error

Fig.1 FTS example of a CPM.

We have fabricated a variety of WCOE shapes in plastics, aluminum, and nickel and its alloys, with a surface finish characteristic of diamond turning (4-8nm RMS) and profile accuracy limited only by the number of iterations we were willing to pursue. Metrology of WCOE is performed on our TalySurf profilometer to validate the fabrication process. Either line traces or full surface scans are performed. Fig.1 shows a linear profile of a simple CPM, and a profile error from a best-fit cubic of an early iteration of the FTS cut in aluminum. Analysis of freeform profile errors is generally more involved and less intuitive then that used for axially symmetric parts; in this case however the simplicity of the shape and symmetry of the error lead us clearly to turning problems (as opposed to FTS).

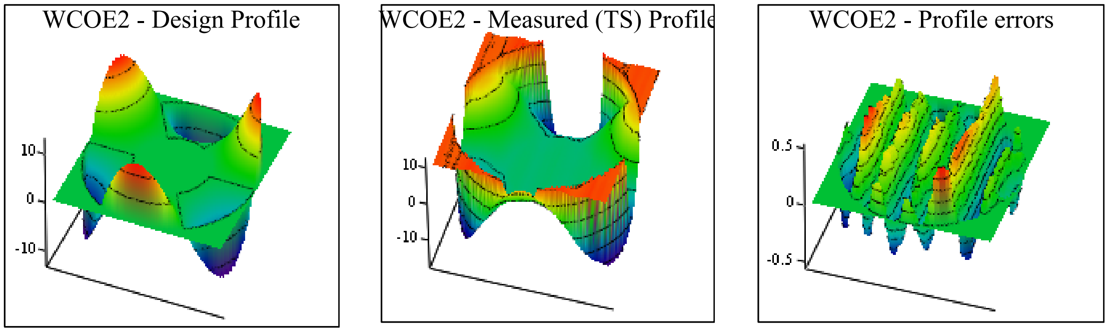


Fig.2 Surface profile of a WCOE2

Fig.2 shows a surface profile and errors of a WCOE of the $z(r,\phi)=P(r)\cdot M(\phi)$ kind; profile errors clearly indicate a measurement problem, not a part error. The residual errors could be traced to the pitch of the lead-screw of the secondary (Y) axis of the profilometer, stressing again the inadequacy of available metrology tools.

Fabrication of Free-Form Optics for Projection systems

Rear-screen projection systems, if designed in a compact form, require complex optics which might include anamorphic and freeform lenses and mirrors. Fabrication of those components is quite challenging, particularly due to their large size. The following is an account of an approach we took to fabricate free-form components of a prototype projection system designed by one of our clients.

The design achieved compactness by incorporating two mirrors and off-axis projection, which necessitated a free-form surface on one of the mirrors and an addition of a free-form corrector lens in front of the projector objective. Both elements had a plane of bilateral symmetry. We used our Moore Nanotech 350FG in a Diamond Milling configuration with a flycutter mounted on the spindle representing a toroidal material removal tool (126mm diameter with a 3mm radius diamond tool, 3000RPM). The tool path was calculated for a raster pattern, which was parameterized in terms of cutting feedrate and raster-line separation to yield a desired surface finish.

The corrector lens was machined in PMMA; it had 30x50mm^2 machined surface area with approx. 5.6mm sag variation. We chose 20nm (PV) surface finish as a target for machining parameters; although we perceived it as marginal, this choice was necessary to meet the delivery time. The resulting machining time was 13 hours (single pass) – a convenient time period for unattended overnight operation.

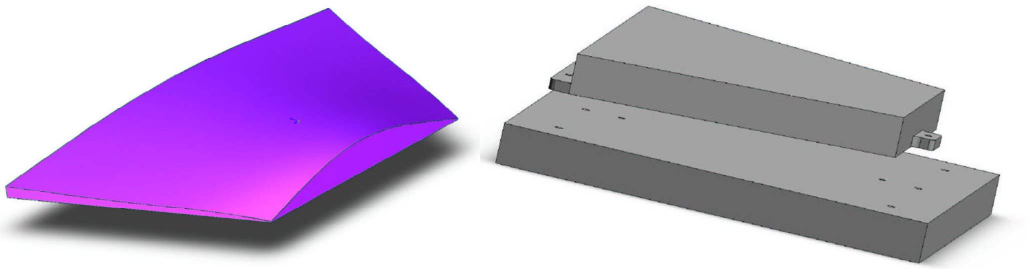


Fig.3 Mirror shape (left) and fabrication assembly (right)

The free-form mirror was machined in aluminum. It had a trapezoidal shape (see Fig.3) with the largest dimension far exceeding the machine capability (474x299 mm envelope), precluding continuous machining of the surface; the sag variation was 36mm. We have separated the machining process into two parts along the symmetry plane of the surface, and fixtured it so that a simple rotation of the mirror in the plane of the common mounting base brought either side of the mirror within the programmed shape. A care was given to assure that both sides match in programmed origin, and we do not have errors associated with angular misalignments of the base.

The choice of machining parameters, which determine the surface finish, was resolved in favor a reasonable machining time and therefore compromised the surface finish. We insisted on one day (or rather "overnight") machining per side because of delivery time constraints. The resulting calculated surface finish was 2μ (PV), which necessitated post-polishing.

No metrology was performed on either part due to the delivery time constraints. They performed as expected in the system.

Conclusions

We have presented two fabrication examples of non-symmetric optical elements. We used fabrication techniques which we refined over many years of use. Our implementation of Fast Tool Servo was applied in the fabrication of Wavefront Coding optical elements with satisfactory results and proved its usefulness in quick setup and fabrication time. Diamond Milling was applied to large freeform optics with very good results. Existing metrology tools are not well suited for freeform optical surfaces, particularly larger ones.

References

[1] W.T. Plummer, J.J. Mader, J.W. Roblee, and J. Van Tassell, "Precision Engineering at Polaroid", Proceedings of the 8-th International Precision Engineering Seminar, Compiégne, France (1995)

[2] Y.E. Tohme and J.A. Lowe, "Machining of Freeform Optical Surfaces by Slow Slide Servo Method", Proceedings of the ASPE 2003 Annual Meeting, Portland, Oregon

[3] The CDM Optics, Inc. website www.cdm-optics.com provides an extensive review of the Wavefront Coding technology.

[4] E. R. Dowski and W.T. Cathey, Applied Optics, vol. 34, no 11, pp. 1859-1866, April, 1995.

[5] Two of the authors (JM, DC) were intimately involved in developing the free-form fabrication technology while at Polaroid, in particular the free-form abrasive grinding.