Fabricating and Testing Freeform Optics: Current Capabilities, Lessons Learned and Future Opportunities

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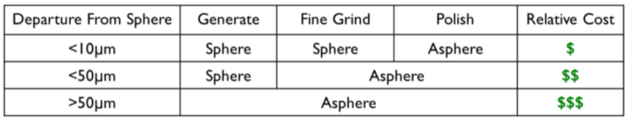
Abstract: Freeform optical shapes or optical surfaces that are designed with non-symmetric features are gaining popularity with lens designers and optical system integrators. A common question about freeform optics is, "If I design it, can you really make it?" This paper will overview a freeform optical fabrication process that includes generation, high speed VIBE polishing, sub-aperture figure correction, surface smoothing and testing of freeform surfaces. This paper will briefly highlight the progress made to each of the processes as well as the challenges associated with each of them.

OCIS codes: (220.0220) Optical design and fabrication; (220.4610) Optical fabrication

1. Current freeform optical manufacturing and testing processes

The optical manufacturing process for a freeform is similar to that of a highly complex asphere. One way to describe asphere complexity is to examine the departure from the best fit sphere increases.[1, 2] Departure from a best fit sphere can determine the manufacturing process used to make the asphere. Table 1 depicts in general terms how the manufacturing process changes for an asphere as the departure increases. For example, aspheres with mild departure allow the manufacturer the ability to generate a sphere and polish in the aspheric profile.



Departure From Sphere	Generate	Fine Grind	Polish	Relative Cost
<10µm	Sphere	Sphere	Asphere	$
<50µm	Sphere	Asphere		$$
>50µm	Asphere			$$$

Table 1: General optical manufacturing processes for aspheres as a function of departure from best fit sphere. [Departure values are guidelines not rules.]

Aspheric departure from a best fit sphere is only one aspect of asphere complexity. Surface form and local slope change are also factors that influence asphere complexity. In general terms, a convex asphere is easier to manufacture than a concave asphere due to grinding/polishing tool geometry limitations, yet concave aspheres are easier to measure than convex aspheres. Figure 1 shows a graphic that simply portrays the increasing complexity of aspheres comparing concave and convex aspheres and a category of aspheres referred to as "gullwings". Gullwing aspheres include inflections on the optical surface or a change in slope on the optical surface; these complex aspheres essentially contain both concave and convex aspheres on the same surface.[3]

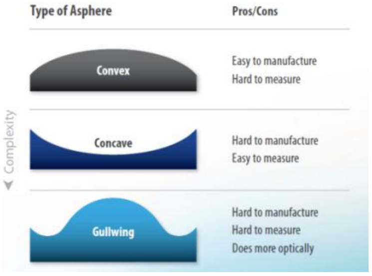


Figure 1: Graphical representation of increasing complexity of aspheric surfaces

All of the aspheres mentioned above have the advantage of rotational symmetry. The biggest distinguishing feature of a freeform surface over an asphere is a lack of symmetry. Non-rotational symmetry increases the demands placed on the manufacturing and testing process.

The freeform optical manufacturing and testing process presented here introduces the freeform surface profile in the initial surface generation. Figure 2 shows our general freeform manufacturing and testing process. Depending on the surface shape and tolerances, all or some of these steps are required. For example, for the freeform surface shown in Figure 3, only the first three steps of the process were necessary due to the surface specifications (< 10µm PV form error). Generation of the shape was necessary. Figure 3 is a photograph of the freeform being generated and the associated full aperture form error measured on a scanning probe coordinate measuring machine (CMM) after generation. Figure 4 is a photograph of the same optic being pre-polished using the VIBE polishing along with the form error over the clear aperture of the surface after VIBE polishing. The general form was held while smoothing the higher frequency noise. Two of the main benefits of the VIBE process are the high speed associated with the process and the ability to maintain the form introduced during generation.[4, 5]

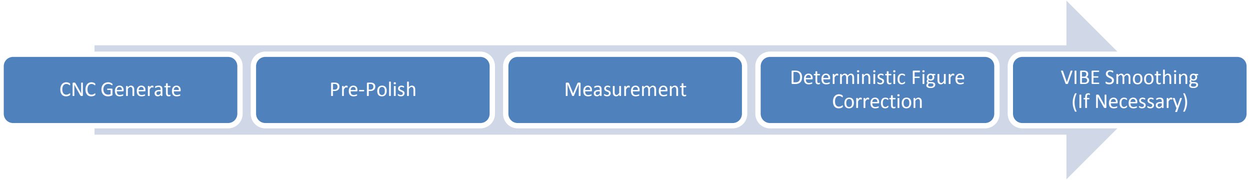


Figure 2: Freeform optical manufacturing and testing process

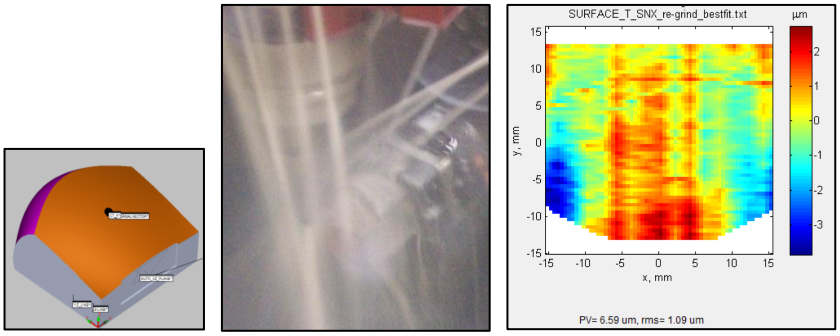
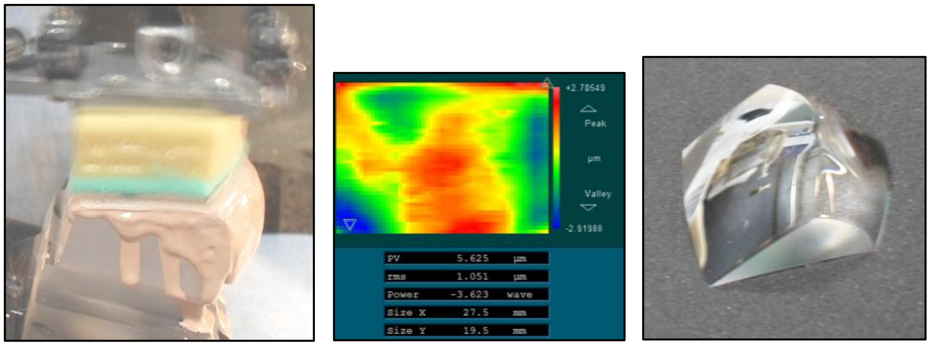


Figure 3: Computer model of the freeform optic (left), photograph of the freeform surface being generated (center) and the resulting surface form after generation (right)



PV	5.625	µm
rms	1.051	µm
Power	-3.623	wave
Size X	27.5	mm
Size Y	19.5	mm

Figure 4: Photograph of the VIBE polishing process (left), the resulting surface form after polishing (center) and a photograph of the final polished surface (right)

The form error after the VIBE polishing process is limited to the form accuracy of the generation process. In order to achieve higher precision freeform surface, sub-aperture deterministic polishing processes are necessary.[6, 7] Deterministic polishing processes are dependent on the metrology method used to measure the initial figure error. The area of freeform metrology is currently under investigation by a number of different research groups.[7-10] Achievable surface form error of freeform surfaces is a function of the complexity of the shape and the uncertainty of the measurement method. A typical scanning probe coordinate measuring machine is limited to approximately ±1 µm PV form error.[10]

Surface smoothing may or may not be necessary based on the application and the severity of resulting mid-spatial frequency errors on the surface. Smoothing can be done implementing the VIBE smoothing process.[11]

2. Lessons learned and future opportunities

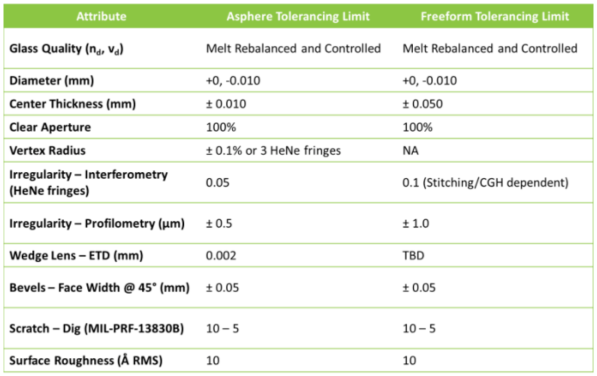
As mentioned earlier, freeform optical manufacturing is similar to high departure and complex aspheres, which implies that many of the same challenges apply, such as a minimum local concave radius and maximum sag to allow for tool clearances. Also similar to aspheres, during manufacturing the freeform surface is oversized in diameter/aperture. It is important that the surface continues to be "well behaved" outside the clear aperture to avoid exotic or undefined surface changes just beyond final aperture.

Measurement is a gating item. Initial work shows that various measurement platforms correlate, but discrepancies at low orders remain.[10] Although significant progress has been made in this area, additional research is required in order to ensure the capability of fractional wave freeform surfaces.

In addition to reducing freeform measurement uncertainty, questions have arisen around specifying and controlling the surface form. A few of these questions include: How is radius error separated from irregularity? How is alignment error separated from irregularity? How is wedge defined for a freeform? How is thickness measured and defined? One key lesson learned while encountering these questions is the importance of physical datums to help control and minimize alignment and machine registration errors.

3. Conclusion, Future work and an Optical Manufacturer's perspective on freeform optic tolerances

In conclusion, Table 2 compares current asphere tolerance limits to freeform tolerance limits, which can be used as a guideline for determining feasibility of including freeforms in optical designs. This table also highlights key areas of room for future work, such as better definition and control of (center) thickness and wedge. Irregularity or form error is also highly dependent on the measurement method available, improvements in this area can be made for both manufacturing and testing to allow for fractional wave freeforms. Current and future work is planned to push these limits to the next level.



Attribute	Asphere Tolerancing Limit	Freeform Tolerancing Limit
Glass Quality (n_d, v_d)	Melt Rebalanced and Controlled	Melt Rebalanced and Controlled
Diameter (mm)	+0, -0.010	+0, -0.010
Center Thickness (mm)	± 0.010	± 0.050
Clear Aperture	100%	100%
Vertex Radius	± 0.1% or 3 HeNe fringes	NA
Irregularity – Interferometry (HeNe fringes)	0.05	0.1 (Stitching/CGH dependent)
Irregularity – Profilometry (µm)	± 0.5	± 1.0
Wedge Lens – ETD (mm)	0.002	TBD
Bevels – Face Width @ 45° (mm)	± 0.05	± 0.05
Scratch – Dig (MIL-PRF-13830B)	10 – 5	10 – 5
Surface Roughness (Å RMS)	10	10

Table 2: General list of soft tolerance limits for glass aspheric and freeform optics

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