Fabrication of Freeform Optics

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ABSTRACT

Freeform surfaces on optical components have become an important design tool for optical designers. Non-rotationally symmetric optical surfaces have made solving complex optical problems easier. The manufacturing and testing of these surfaces has been the technical hurdle in freeform optic's wide-spread use. Computer Numerically Controlled (CNC) optics manufacturing technology has made the fabrication of optical components more deterministic and streamlined for traditional optics and aspheres. Optimax has developed a robust freeform optical fabrication CNC process that includes generation, high speed VIBE polishing, sub-aperture figure correction, surface smoothing and testing of freeform surfaces. Metrology of freeform surface is currently achieved with coordinate measurement machines (CMM) for lower resolution and interferometry with computer generated holograms (CGH) for high resolution irregularity measurements.
Keywords: Freeform, optics, manufacturing, VIBE, metrology

1. INTRODUCTION

Freeform optics have become a popular tool with optical engineers and integrators for imaging and illumination applications.[1-4] These optical surfaces lack radial symmetry and may have complex shapes that solve a variety of optical design problems. However, the availability of freeform optics has been limited by the manufacturing and testing of these unique optics.

In traditional optics manufacturing, the optic is created by lapping the correct radius using dedicated tooling, followed by pitch polishing in a slow iterative process. The introduction of CNC optics manufacturing replaced the need for specialized tooling and created a more deterministic process.[5]

The manufacturing process of freeform optics is similar to that of complex aspheric optics. The process steps are best estimated by the amount of departure from a best fit sphere.[6] Table 1 shows the how the general manufacturing process changes for aspheres as departure from sphere increases. Surfaces with small departures from the best fit sphere may use traditional manufacturing and measurement steps. The manufacturing process may change as the departure from a sphere increases.

Departure from Sphere	Generate	Fine Grind	Polish	Cost
<10um	sphere	sphere	sphere	$
<50um	sphere	asphere	aphere	$$
>50um	asphere	asphere	asphere	$$$

Table 1: Optical Manufacturing process for aspheres as a function of departure from sphere

Aspheric departure from a best fit sphere is only one aspect of asphere complexity. Surface form and local slope change are also influencing factors. 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.[7]

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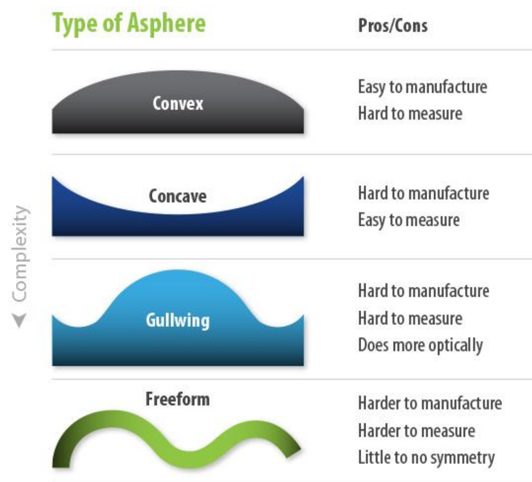

Figure 1: Aspheres of increasing complexity and their manufacturing pros/cons

Although aspheres possess complexity in their surface figure, they still obtain manufacturability advantage due to their rotational symmetry. Freeforms, with their lack of rotational symmetry, put increased complexity and demands on the manufacturing and metrology of the optics.

2. MANUFACTURING PROCESS

The manufacturing of freeform optics follows the same general manufacturing process as other precision optics. This process has evolved over the years as the sophistication of the fabrication equipment also evolved. The general manufacturing and testing process is shown in Figure 2. Parameters such as surface shape and tolerancing determine if all steps are required. This section will describe the manufacturing steps in more detail.

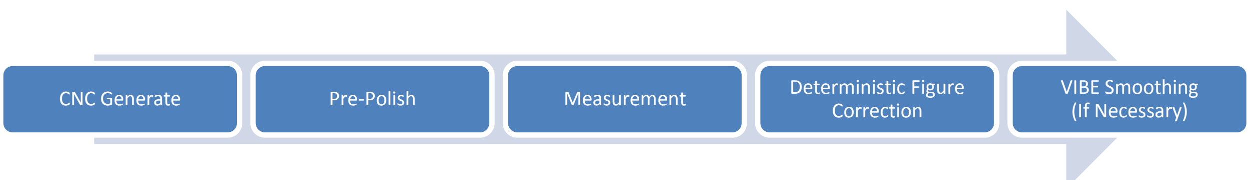

Figure 2: Freeform optical manufacturing and testing process

2.1 Generation

The initial step in the manufacturing of freeform optics is to generate the surface on a CNC machine (Figure 3). A multi-axis CNC machine with diamond tooling is required to generate most freeform surfaces. The surface figure after generation may still have errors due to factors such as machine tool errors, tool wear, and alignment errors. A generation correction step has been introduced into this process to correct for these common manufacturing errors by programming the CNC machine to generate a new surface which is the sum of the original nominal shape and the measured error. This process reduces the overall surface errors after the final generation step.

Figure 3: CNC generation process

2.2 Polishing

After generation the next step is polishing, which removes the sub-surface damage introduced by the generation process.[8] Full-aperture polishing of freeform surfaces is often challenging, we have addressed this by developing VIBE polishing.[9] VIBE polishing has several advantages: full aperture to increase material removal rates, fast to increase material removal rates, custom compliant active layers as well as minimize change to the surface form. It has been shown that VIBE can remove material 10-50x faster than conventional polishing.[10] Figure 4 shows the VIBE polishing process and the results of 60 second VIBE polish run in Figure 5.

Figure 4: VIBE full-aperture polishing of freeform conformal window

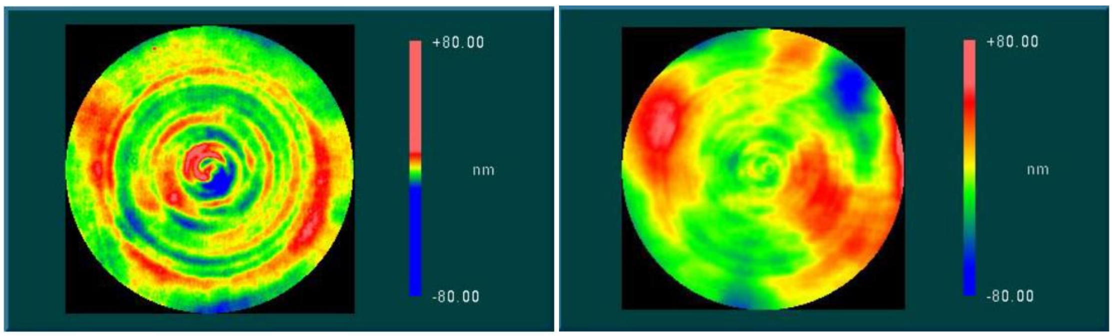

Figure 5: Initial polished surface (left) and surface after 60-second VIBE polishing (right)

2.3 Sub-aperture Figure Correction

The principle function of sub-aperture polishing is to correct the figure of the two typical methods of sub-aperture figure correction shown in Figure 6, Zeeko's bonnet polishing and QED MRF (magneto-rheological fluid) polishing. In both methods there is only a small portion of the part in in contact with the polishing tool. When given the error map of the part, the CNC machine scans across the part and varies removal rate to remove material at the specified locations. This technique used to produce accurate surface figure is well-matched for CNC machines. Figure 7 shows an example of sub-aperture figure correction on a freeform conformal window, 93 mm diameter. The peak-to-valley error was reduced after each run.

Figure 6: Two example methods of sub-aperture figure correction: left: Zeeko's bonnet polishing and right: QED's MRF polishing

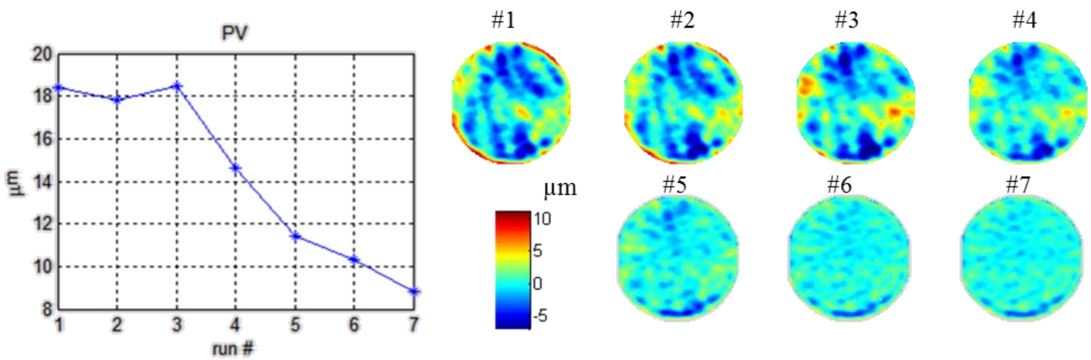

Figure 7: Example of a sub-aperture figure correction on atoroid conformal window (93 mm diameter) showing the reduction of the PV error in each run.

2.4 Final Polishing

Although sub-aperture polishing can correct form error, it is prone to residual periodic surface undulations that are referred to as mid-spatial frequency (MSF) errors.[11] The size and periodicity of these tooling marks, dependent on the machine platform by which they were polished, can range from 1 – 50 mm periods. As a final finishing step, the same VIBE technique used in the initial polish process may be used to reduce mid-spatial frequency errors. Figure 8 shows the improvement of the mid-spatial frequency errors on a freeform conformal window using the VIBE.

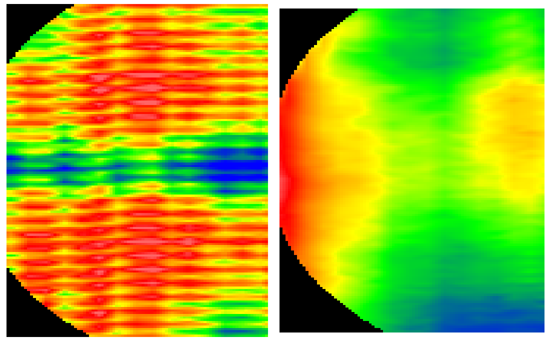

Figure 8: Freeform window with large MSF error (left) and same part after VIBE final polishing (right)

3. FREEFORM METROLOGY

In any manufacturing process, measurement data is critical for successful convergence. The accuracy and resolution of the metrology data will determine the accuracy of the final part and leads to the adage "*you can't make it unless you can measure it*". The manufacturing process steps described in this paper are altered depending on the metrology needed to fulfill the parts' specifications. The process of sub-aperture polishing requires an accurate surface map to adequately correct the figure. The challenges for the production of freeform optics are applicable to not only the manufacturing process but the metrology to support such processes. At Optimax, we use the following metrology of freeform optics:

3.1 Coordinate Measurement Machine (CMM)

Optimax measures freeforms and other shapes on a Leitz PMM 866 coordinate measuring machine, shown in Figure 9, with certified volumetric accuracy of 1.2 µm + L/400 µm (where L is in mm). The probe is a ruby sphere attached to a scanning head with constant force near 0.3 N. Typically, surfaces are measured with a series of lines. Along the lines (the direction of the scan), the standard point lateral spacing is approximately 0.5 mm and the lateral spacing between the lines is typically near 1 mm. We typically measure surfaces to within 2 mm of the part edge. These parameters can be adjusted to meet customer specifications. We have measured surfaces up to 250 mm diameter and are confident with measuring up to 400 mm in diameter. The result for a surface measurement on the CMM is an irregularity map showing deviation normal to the nominal shape, like an interferometer. The advantage of the CMM over an interferometric tool is the CMM can measure the surface relative to the part's datum features or best fit to itself (as with an interferometer), shown in Figure 1. In addition, the CMM measures low order errors like power, coma, and astigmatism which could be alignment errors in certain interferometric setups. In general, we have found that the CMM can be used to manufacture parts with irregularity specifications around ±1 µm. The measurement errors include repeatability, mounting, environment, CMM axes errors, and other factors. An example of the CMM reproducibility is shown in Figure 10, showing three measurements of convex toroid surface and a standard deviation map.

Figure 9: Optimax Coordinate Measurement Machine

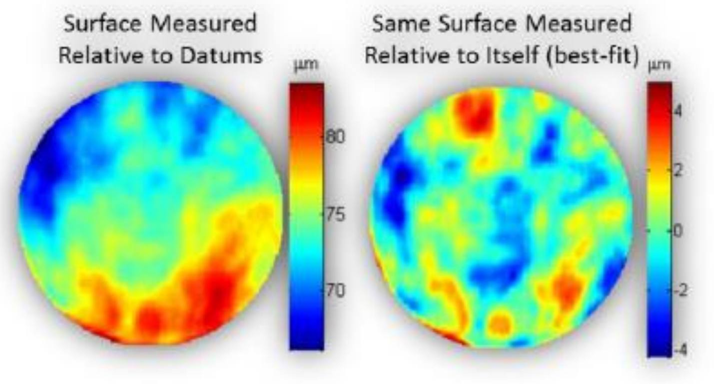

Figure 10: 90 mm Atoroid measured on Optimax CMM showing raw data (left) and the data relative to the best-fit shape (right).

3.2 Interferometry

As stated above, optics can be measured on a CMM with a surface irregularity of approximately ±1 µm. To achieve higher resolutions required for some parts, we have the ability to use interferometry with or without the use of a computer generated hologram (CGH). Interferometry can be used without a CGH when the deviation from a reference sphere is small and can be measured directly (an example is shown in section 4). For larger deviations a CGH can be used for an interferometric measurement of a freeform. A CGH, shown in Figure 11, is a diffractive element that transforms a spherical wavefront of a standard interferometer into a wavefront that matches the nominal shape of the part under test. The CGH shown in Figure 11 was made to match an off-axis parabola. The resultant fringe pattern in Figure 11 shows the deviation of the measured part from the nominal shape. The interferometer hardware and software is then used to analyze the fringe pattern to result in a height map of the surface. With the example shown here, we were able to produce the off-axis parabola to less than λ/20 peak-to-valley (32 nm). With CGHs, we are able to produce high-precision freeform optics. However, a CGH is unique to the specific part under test and will not work for all freeform shapes.

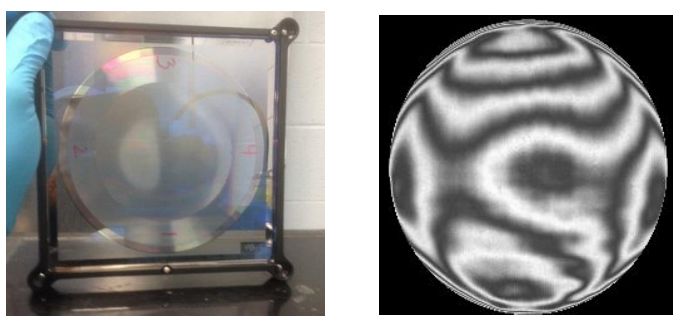

Figure 11: CGH (left) and the resultant fringe pattern showing deviation from nominal (right)

4. MANUFACTURED FREEFORM EXAMPLES

4.1 Freeform Prism

Shown in Figure 12 (left) is a computer model of the freeform prism to be manufactured. Due to the surface specification of < 10 µm of PV form error, only the first three steps in the manufacturing process were necessary. Figure 12 (middle) shows the prism in the first step of shape generation on multi-axis CNC machine. The full aperture surface error map is shown in Figure 12 (right) measured by a scanning probe CMM.

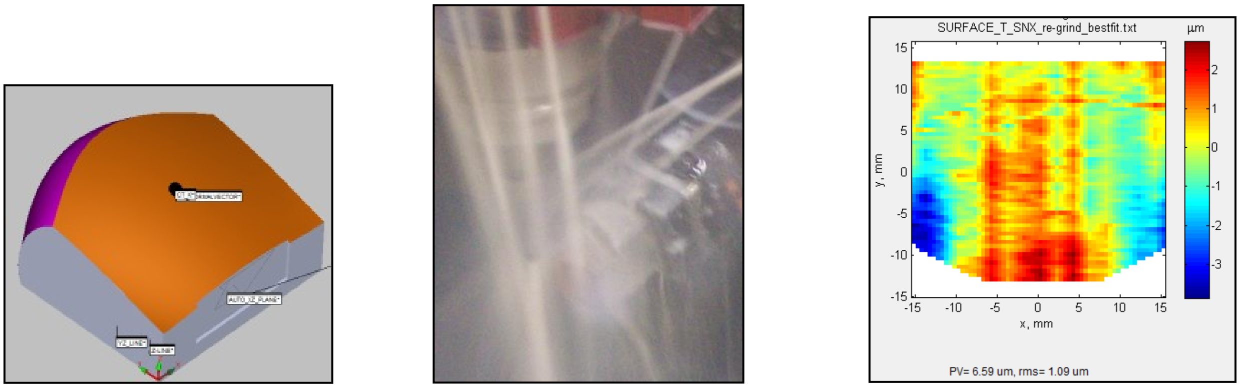

Figure 12**:** Computer model of freeform prism (left) prism in generation step (middle) and full-aperture error map measured on CMM.

Due to the mid-spatial frequency errors shown in Figure 13 (right) the prism was VIBE polished. Figure 13 (left) shows the optic during VIBE polishing. The mid-spatial frequency errors were greatly improved as shown in Figure 13 (middle); the surface error map after the VIBE polishing process step. The final freeform optic is shown in Figure 13 (right).

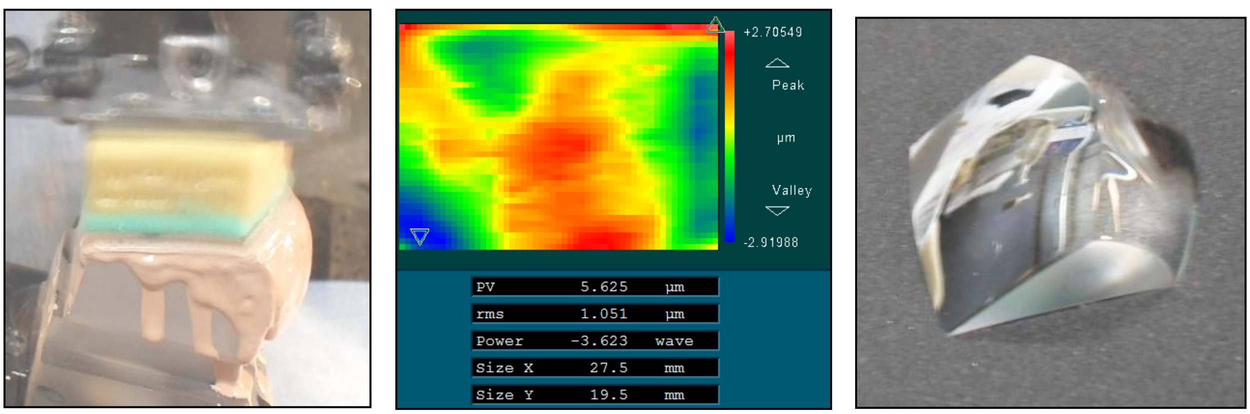

Figure 13: Freeform prism during VIBE polishing (left) surface error map after polishing (middle) and final freeform optic (right)

The freeform prism had commercial quality tolerances. To achieve higher precision in a freeform surface sub-aperture deterministic polishing is necessary. The processes of deterministic polishing are dependent on the metrology method used. When the freeform surface has small departures from a reference wavefront higher accuracies can be achieved.

4.2 Off-Axis Parabola

In manufacturing of an off-axis parabola, the simplest method of fabrication is to create the main parent paraboloid using techniques typical to rotationally aspheric optics. The off-axis child segment is then drilled out from the parent. However, in some cases the parent may be too large to fabricate and therefore, the child must be fabricated as a stand-alone optic. In this case, the child optic may be considered a freeform optic lacking rotational symmetry. Challenges occur when the surface accuracy needs to be sub-wavelength leading to interferometric measurement.

Figure 14 shows an interferogram of an off-axis parabolic mirror with a 30 mm clear aperture and a 1500 mm radius of curvature. The fringes are produced using a reference sphere in a confocal arrangement. Since this a relatively high f-number (i.e. slow) optic, the deviation from a reference sphere is measurable on the interferometer since the fringe frequency stays within Nyquist.

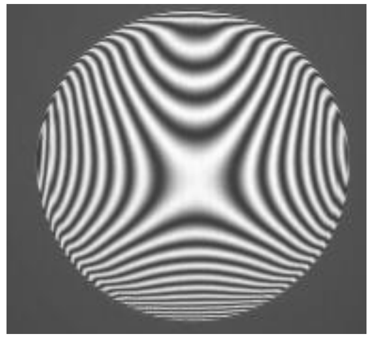

Figure 14: Fringes produced from an off-axis parabola interfering with a reference spherical wavefront

Figure 15 (left) is the calculated wavefront map showing the part is measurable against a spherical wavefront and has ~2.5 waves of deviation from a sphere. By subtracting the nominal shape software the deviation from perfect surface can be calculated. In an iterative process the error map is fed to a sub-aperture polishing machine to deterministically correct the surface. Figure 15 (right) is the final measurement showing the finished part at $\lambda/40$ P-V irregularity.

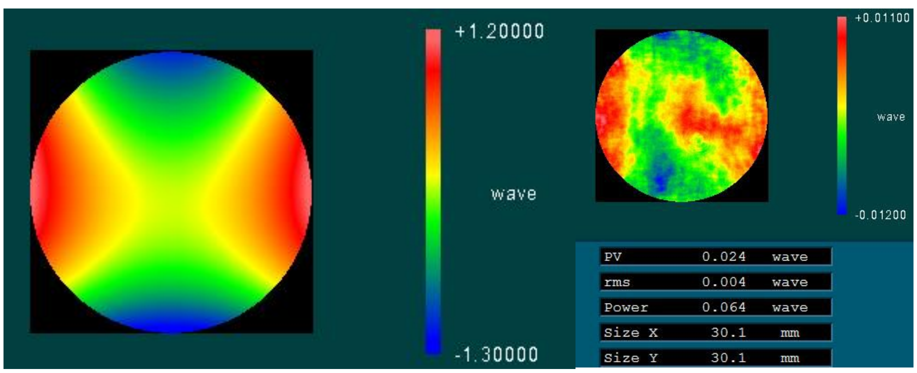

Figure 15: Calculated wavefront map of off-axis parabola (left) deviation from nominal after post-processing (right)

4.3 Anamorph

In contrast to an off-axis parabola with slight deviations from a sphere, is an anamorph shown in Figure 16 (left). An anamorph has bilateral symmetry in both X and Y sections and is described by the equation

$$Z = \frac{C_x X^2 + C_y Y^2}{1 + \sqrt{1 - (1 + K_x)(C_x^2 X^2) - \left(1 + K_y\right)\left(C_y^2 Y^2\right.}} + AR[(1 - AP)X^2 + (1 + AP)Y^2]^2 + BR[(1 - BP)X^2 + (1 + BP)Y^2]^3 + CR[(1 - CP)X^2 + (1 + CP)Y^2]^4 + DR[(1 - DP)X^2 + (1 + DP)Y^2]^5$$

Where $C_x, K_x, C_y, K_y, AR, BR, CR, DR, AP, BP, CP, DP$ are constants

This part has a clear aperture of 50 mm with a sagittal height of 16 mm. Even at this large aspect ratio, the peak-to-valley surface irregularity was measured to be ~ 5 um measured on a CMM. The surface data is shown in Figure 16.

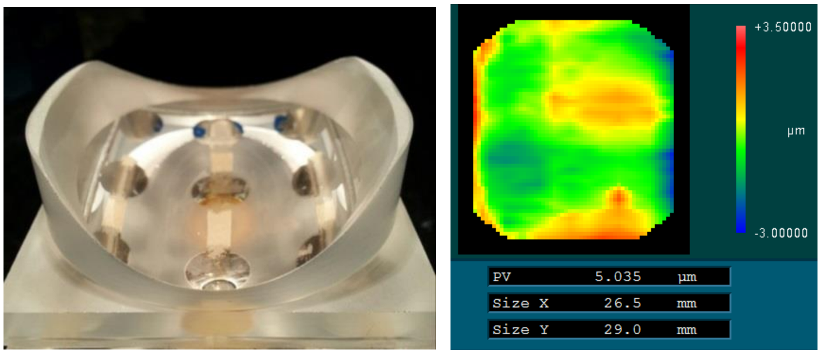

Figure 16: Anamorph with clear aperture of 50mm and sagittal height of 16 mm (left) and the irregularity measured on a CMM (right)

5. CONCLUSION

Freeform optics have proven to be a significant advancement to optical design and system performance. At the same time, process and metrology are challenging for optical manufacturers. We have shown an overview of the optical manufacturing process that leverages our VIBE full-aperture polishing for freeforms and metrology to verify specifications. As metrology continues to improve, freeforms will obtain the accuracy of traditional optics.

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