# DEVELOPING CAPABILITIES FOR FABRICATING EXTENDED POLYNOMIAL FREEFORM MIRRORS

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## INTRODUCTION

An optical system has been designed at Sandia National Laboratories that includes an extended polynomial freeform mirror. The envisioned mirror is described by a polynomial series in X and Y such that the best fabrication method is direct machining via slow tool servoing where the desired surface geometry is generated by synchronizing linear tool position (X, Y, Z) with spindle position (theta). The fabrication and metrology of freeform surfaces involves complex processes with numerous inputs and potential error sources. Therefore, standard axis-symmetric surface geometries were fabricated in a nonstandard, non-rotationally symmetric form in order to generate and demonstrate fabrication and metrology processes for more arbitrary freeform geometries. Prior research in fast tool servo[1] and slow tool servo[2,3] equipment development have relied on tilted flats and off-axis parabolas since they facilitate the machining of non-rotationally symmetric surfaces that can be oriented to leverage on-axis metrology techniques. Such complexity in fabrication and simplicity in metrology prompted their use in the recent work.

## OFF-AXIS OPTIC SURFACE REQUIREMENTS

The desired extended polynomial freeform can be described by the equation

$$z = \frac{R_c r^2}{1+\sqrt{1-(1+k){R_c}^2 r^2}} + \sum_{i=1}^{N} A_i E_i(x,y)$$

where $z$ is the surface sag at position $x$, $y$, $r$ from the optic center apex, $k$ is the conic coefficient, $R_c$ is the radius of curvature, $A_i$ is the coefficient on the $i^{th}$ extended polynomial term, $N$ is the number of polynomial terms in the series, and $E_i(x,y)$ represents the $i^{th}$ order power series term in $x$ and $y$. The final design prescription for the desired optical surface was based on a 5$^{th}$ order polynomial where optical system requirements

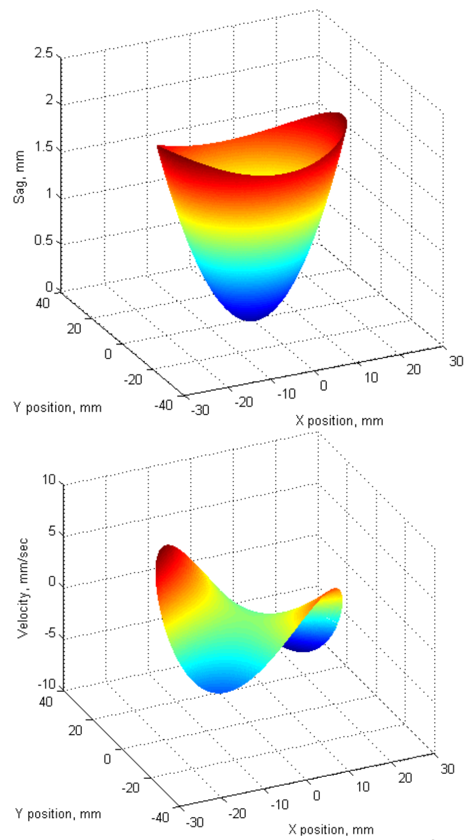


*FIGURE 1. The extended polynomial freeform surface and its z-axis velocity profile.*

necessitate a surface form accuracy better than 1 µm and a surface finish better than 5 nm Sa. Figure 1 shows the desired surface geometry and resultant z-axis velocity profile for slow tool servoing. The optic has an aperture diameter of 41.35 mm, a sag of 2.02 mm, and a maximum rotational asymmetry of 417 µm at its aperture diameter. The maximum z-axis tool velocity required during cutting is 6.46 mm/sec. While the tilted flat and off-axis parabola cut during process development did not replicate the same asymmetrical departure as that of the final freeform design, they were representative of early design revisions and were found adequate

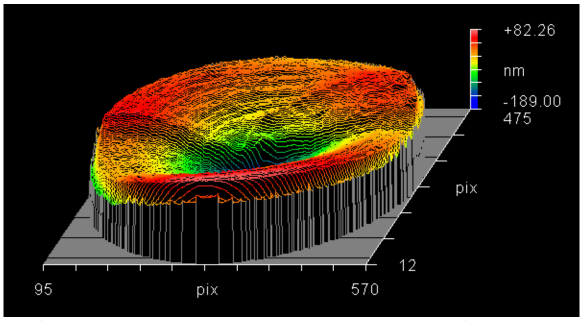


*FIGURE 2. 0.271 µm peak-to-valley form error for the tilted flat.*

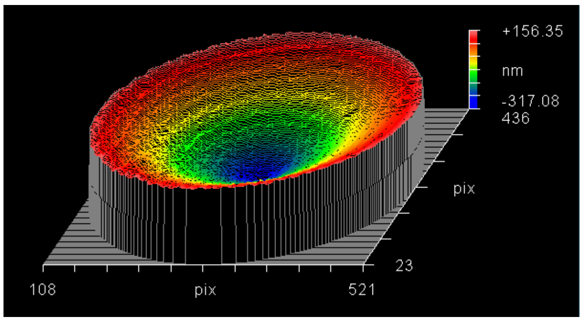


*FIGURE 3. 0.473 µm peak-to-valley form error for the face cut flat.*

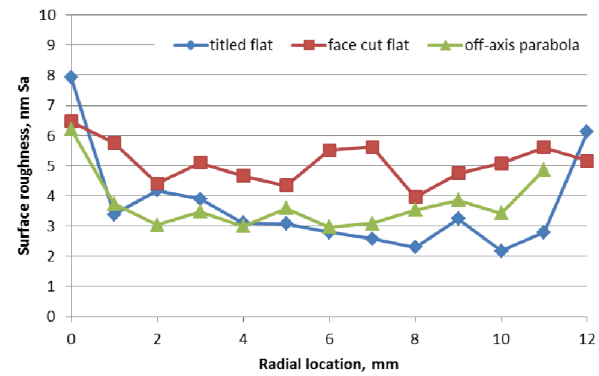


*FIGURE 4. Surface finish verses radial position for each test workpieces.*

for examining the form accuracy and surface finish that could be achieved through slow tool servoing. Cutting experiments were all performed on 5 mm thick, ½ hard, alloy 464 naval brass due to its low tool wear and excellent surface finish under diamond turning. Rough cutting on each of the test workpieces was performed using a 0.244 mm radius diamond tool with the final surface being machined using a single finish pass with a 0.38 mm radius diamond tool.

## TILTED FLAT FABRICATION

Process work began with the tilted flat as it was the simplest geometry to program, to fabricate via slow tool servoing and to measure in a standard manner via on-axis form interferometry. The initial concern raised in process evaluation was whether the cutting speeds required for slow tool servoing would generate surface finishes that met system requirements. Since slow tool servoing requires coordinated motion of the z-axis with the x-axis and the work spindle, cutting velocities decrease with increases in the asymmetric departure and can therefore be more than an order of magnitude lower than that utilized in traditional turning operations. Subsequently, questions were raised regarding the potential for degradations in the material removal process (ex. tearing or burr formation), in the behavior of the cut material (ex. chip buildup or scratching) or in the rate of tool wear.

A 25.4 mm tilted flat was cut with 100 µm of rotational asymmetry at its OD which required a maximum z-axis velocity of 0.84 mm/sec. For comparison, a 25.4 mm flat was machined via traditional face turning under typical process feeds and speeds. While the cutting velocity for the tilted flat varied with both x-axis and spindle position, its maximum spindle speed was on the order of 170 rpm with a finish cross feed rate of 1 µm/rev and a depth of cut of 10 µm. The face cut flat, however, was finish machined at 2000 rpm using a cross feed rate of 1.5 µm/rev and a depth of cut of 3 µm. Figures 2 and 3 show on-axis interferometric measurements of the tilted and face cut flats, respectively. Unexpectedly, the 0.271 µm form error of the tilted flat was almost half the 0.473 µm form error of the face cut flat. While the error for the face cut flat was not examined in great detail, its most likely source is believed to be deformation due to vacuum mounting. Figure 4 plots surface finish across the radius for the flats and the off-axis parabola. No degradation was observed during slow tool servoing as the surface finish for the face cut flat was generally rougher than that of the tilted flat, except at part center where both cutting processes produce a cutting velocity that approaches zero. Both flats exhibited roughness values, however, near or below the system requirement of 1 nm Sa. While a secondary polishing step is unnecessary at this time, system characterization will evaluate whether further improvements are necessary.

## OFF-AXIS PARABOLA FABRICATION

After examining the machining of the tilted flat, an off-axis parabola was fabricated to examine a

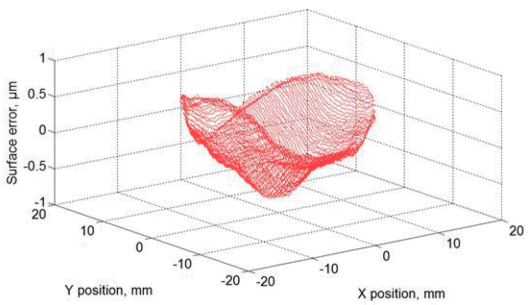

*FIGURE 5. 0.96 µm peak-to-valley form error for the off-axis parabola.*

surface that more closely represented the desired freeform geometry. While a parabolic section can be cut in a rotationally symmetric manner, the part was defined in an off-axis frame, rotated about its center surface normal. Measurement and testing of the resulting parabolic mirror are straightforward since a parabola is well understood both geometrically and optically. As with the tilted flat, the parabola was fabricated while the optical design was still changing; and therefore, did not represent the final surface as originally intended. The off-axis parabola used a $6^{th}$ order extended polynomial series centered in the off-axis pupil such that focus was 20 mm off axis with a tilt of roughly 17.5°. It had a 25.4 mm outside diameter, a sag of 1.18 mm and a maximum asymmetric departure of 176 µm. Its maximum z-axis travel velocity during cutting was 2.53 mm/sec.

The part was cut via slow tool servoing using a finish cross feed of 1 µm/rev, a depth of cut of 5 µm, and a maximum spindle speed of approximately 170 rpm. Figure 5 shows the 0.96 µm surface form error obtained on Sandia's F-25 micro-CMM. While the measurement uncertainty for the F25 is roughly 250 nm; workpiece deformation under vacuum mounting, diamond tool offset errors, motion errors during slow tool servoing and micro-CMM probe offset errors are other sources for the observed form error whose individual contributions were not quantified. Work was performed to quantify potential errors between the optical model and the 3D solid models utilized during metrology. Analysis showed model correlation to better than 70 nm, significantly less than the observed errors. While the form error did increase over both the tilted flat and the face cut flat, it remains within the requirements for the optical system. As with the tilted flat, Figure 4 shows that the finish across the part radius remains at or below the 5 nm Sa finish requirement. The part has also been tested optically using a HeNe laser to see that it properly focuses a collimated input. While focal distance has not yet been measured the focused spot diameter is roughly 10 µm, suggestive of diffraction limited performance. Interferometric data has also not been collected, but is planned in continued work.

## CONCLUSIONS

Off-axis optics have been utilized to develop and evaluate a slow tool servo fabrication process for an extended polynomial freeform mirror. Surface requirements of 1 µm for form accuracy and 5 nm Sa for surface finish have been demonstrated on representative tilted flat and off-axis parabola surfaces. Remaining work will fabricate and measure the desired freeform mirror for implementation in a first prototype system.

## ACKNOWLEDGEMENTS

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