# Development of optimal grinding and polishing tools for aspheric surfaces

J. H. Burge, B. Anderson, S. Benjamin, M. Cho, K. Smith, M. Valente

Optical Sciences Center
University of Arizona, Tucson, AZ 85721

## ABSTRACT

The ability to grind and polish steep aspheric surfaces to high quality is limited by the tools used for working the surface. The optician prefers to use large, stiff tools to get good natural smoothing, avoiding small scale surface errors. This is difficult for steep aspheres because the tools must have sufficient compliance to fit the aspheric surface, yet we wish the tools to be stiff so they wear down high regions on the surface. This paper presents a toolkit for designing optimal tools that provide large scale compliance to fit the aspheric surface, yet maintain small scale stiffness for efficient polishing.

**Keywords**: optical fabrication, aspherics, polishing technology

## 1. INTRODUCTION

Most optics are made with spherical surfaces because these surfaces are simple to describe, straightforward to manufacture, and easy to measure. A spherical surface can be specified by a single parameter – its radius of curvature *R*. The spherical surface is the most natural shape to manufacture because of its symmetry. Spherical shapes always tend to result from a condition where the two surfaces are rubbed together randomly with an abrasive medium so they wear each other down. For optical surfacing, the lap and the optical surface tend to wear on their high spots, and since both are in constant motion about several axes, they will both tend to be spherical. Any other shape would present a misfit between the two, which would tend to be worn down. The fine polishing requires intimate contact between the lap and the optic, and this naturally occurs when both are spherical with matching radii. Testing of spherical surfaces also takes advantage of the symmetry.

Spherical surfaces are not usually the optimal shape for lens surfaces or for mirrors for most optical applications. Optical systems can benefit tremendously if they can use aspherical surfaces – surfaces that are not spherical. The use of aspheres allows better quality images with the use of fewer elements. The application of aspheric surfaces is limited to a tiny fraction of optics because of the difficulty fabricating and testing these surfaces.

The polishing tool provides a key element for manufacturing aspheric surfaces. Unlike the case for spherical surfaces, the tool for working aspheres must change its shape as it rotates and moves across the optic. As it does so, it must also maintain intimate contact with the surface. The optic is most efficiently worked using large, stiff tools, as long as they fit the asphere. However, tools that are small and compliant will always fit the best. The difficulty of designing tools for aspheres is to provide enough stiffness and size for the tools to work efficiently, yet enough flexibility for the tools to fit. We present two classes of such tools.

---

Contact information:
jburge@optics.arizona.edu 520-621-8182
bill.anderson@optics.arizona.edu 520-621-2787
scott.benjamin@optics.arizona.edu 520-621-4875

Optical Manufacturing and Testing IV, H. Philip Stahl, Editor, Proceedings of SPIE Vol. 4451 (2001)

## 2. GRINDING AND POLISHING TOOL DESIGN FOR ASPHERICS

Before discussing the tool design, it is important to understand the principles behind grinding and polishing. In general, grinding and polishing are both lapping operations, which uses two surfaces, the lap and the optical surface, rubbing against each other. An abrasive medium is maintained between these surfaces causing both to wear. For grinding, a coarse abrasive medium, such as aluminum oxide or silicon carbide grit is used, and the lap is made of something hard, like tile, glass, or metal. The grit acts to wear the surfaces down by making tiny fractures that cause small pieces of the optic to chip out. The amount of removal can be controlled by setting the pressure, speed, or time spent on any particular part of the optic. The resulting surface is rough on small scales, and provides a diffuse, rather than specular reflection. Polishing is similar, but uses different materials. A polishing slurry such as milled cerium oxide or iron oxide is used with a lap made of pitch, porous plastic pads, or special cloth. The removal mechanism strongly involves the chemistry of the materials, and it results in a smooth surface.

To make an optical surface, the optician must work the surface to control the shape, which is measured by an optical test, using a process that will result in the desired finish. The optician uses two different effects to control the surface shape; natural smoothing and directed figuring. Features that are much smaller than the lap tend to be removed by natural smoothing. The mechanism is shown in Figure 1. As long as the lap is stiff, it will ride over ripples in the surface and only touch the tops, thus wearing them down. This effect is diminished for the case where the errors become as large as the tool, or if the tool is so complaint that it easily bends to conform to the ripples. A semi-rigid tool can work because it conforms to the surface, yet maintains higher pressure for the high zones.

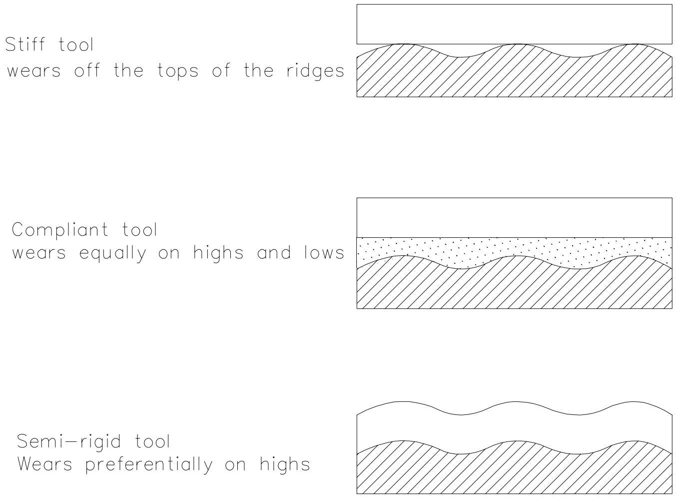


**Figure 1.** Small scale errors are naturally smoothed out using a stiff tool. A very compliant tool does not wear the high zones any faster then the low zones. A semi-rigid tool has some compliance so it conforms to the ripples, but results in higher pressures on the crests than at the valleys.

Features on optical surfaces larger than the polishing tools can be shaped using directed figuring. This is simply controlling the process based on surface measurements to work on the high areas. In its simplest form, an optician will use directed figuring by making a small tool and running it on the high regions of the optic, as determined by an optical test. This can be augmented with computer controlled machines and coupled with sophisticated software. This type of figuring has been extremely successful.[1]

It is difficult to polish steep aspheres because the large departure of the optical surface from spherical requires the tools to be either very small or very compliant. Tools that are very compliant always fit the surface, but they have insufficient natural smoothing. Tools that are very small always fit, but they are not efficient. It takes many hours of polishing with a small tool to cover the entire surface of a large optic.

The amount of bending required for a tool to fit the surface is calculated from the aspheric departure. If a circular tool is made to fit at the vertex of the asphere, the misfit for the off axis tool is easily calculated in terms of the common modes of optical aberrations: power, astigmatism, and coma. The geometry is shown in Fig. 2 and the magnitude of the misfit is shown in Table 1, where $K$ is the conic constant of the asphere and $R$ is the vertex radius of curvature.[2]

**Table 1.** Peak to valley lap misfit, relative to vertex.

| Power | Astigmatism | Coma |
|---|---|---|
| $\dfrac{Ka^2b^2}{2R^3}$ | $\dfrac{Ka^2b^2}{2R^3}$ | $\dfrac{Ka^3b}{3R^3}$ |

If the polishing tool does not fit the optical surface, then the removal profile will come from only the regions in contact. This is useful when figure errors in the optics cause this misfit because the bumps will tend to be worn down. If the misfit comes from the aspheric shape itself, then polishing will tend to wear grooves into the surface. There are three ways the polishing tool can be made to fit the asphere:

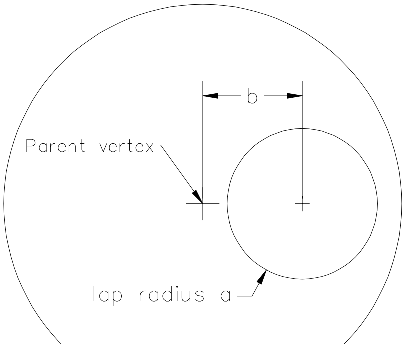


**Figure 2.** Definition of polishing geometry

1 Actively bend the lap into the correct shape. This is accomplished using a stressed lap.[3] This tool, shown in Fig. 3 uses actuators at the edge of a rigid plate to bend the plate so it fits the aspheric surface. As the lap is rotated and stroked across the surface, its shape is changed. Since it is actively controlled, a large lap can be used.[4] This technique has proven to be highly successful for large, fast telescope mirrors.[5]

2. Form the lap into the correct shape with inelastic materials. This is usually done by pressing a pitch lap onto the surface. The pitch will flow so that it fits the surface in that one spot. Then, the tool can be stroked by small amounts without causing excessive misfit.

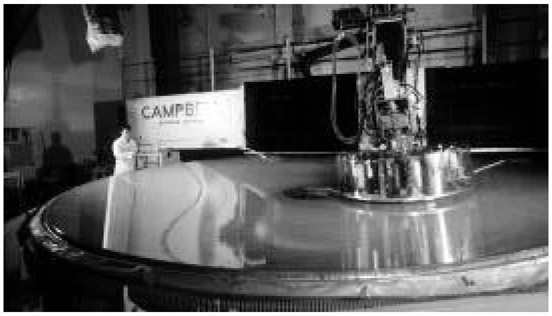


**Figure 3.** Stressed lap polisher working a 6.5-m f/1.25 paraboloidal mirror at the University of Arizona.

3. Press the lap to the surface so it elastically bends into the right shape. If a compliant lap is pressed onto an aspheric surface, a pressure variation under the lap will result, which will tend to bend the lap to fit the asphere. If the compliance is large enough (for the amount of pressure applied) the lap will be bent into the desired shape.

We describe two types of tools that are engineered to have enough compliance in their lower order mode so that they deform elastically to fit the aspheric shape under the modest polishing forces. Yet the tools are stiff over small scales so they smooth out ripples in the surface.

## 3. MEMBRANE TOOLS

A tool faced with a membrane, or thin plate of rigid material can provide local stiffness, yet remain globally flexible enough to fit the aspheric surface. This composite tool, shown in Fig. 4, is made from a membrane with a grinding or polishing interface on one side. The other side is attached using compliant foam that provides the coupling to the spindle, but does not affect the bending. The bending stiffness of the membrane is chosen by selecting the material and the thickness.

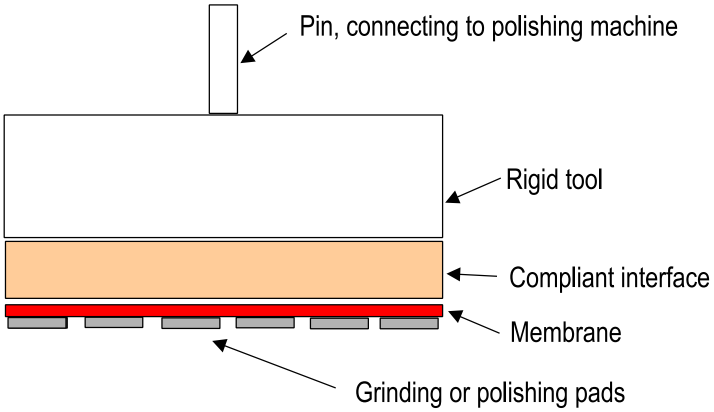


**Figure 4.** Composite tool using a membrane for local stiffness.

The membrane works because it is stiff over small regions. The membrane bending stiffness depends on its thickness $t$, modulus of elasticity $E$, and Poisson ration $\mu$. For the case where the membrane is run over ripples in the surface with P-V surface variation $\Delta z$ and spatial period $L$ , we calculate the pressure variations that would develop under the lap to be

$$\Delta P = \left( \frac{2\pi}{L} \right)^4 \frac{Et^3}{12(1-\mu^2)} \Delta z \, .$$

The lap stiffness can be used to estimate the tendency to smooth out small scale errors. We know that the instantaneous removal rate is proportional to local lap pressure and speed. If the lap is forced to conform to a surface with sinusoidal ripples, the resultant sinusoidal pressure variations applied to the lap from the glass is given above. The high pressures will be on the high zones, which will then tend to be worn down faster than the low pressures on the low zones. Since we are dealing with elastic bending, a complex surface shape can be treated using Fourier analysis, *i.e.* one frequency at a time.

This stiffness is plotted in Figure 5 for four cases where the membrane is made from aluminum with thickness of 0.04 , 0.2, 1, and 5 mm. The stiffness over small scales, evident in the plot, is responsible for the strong smoothing tendency for this type of lap.

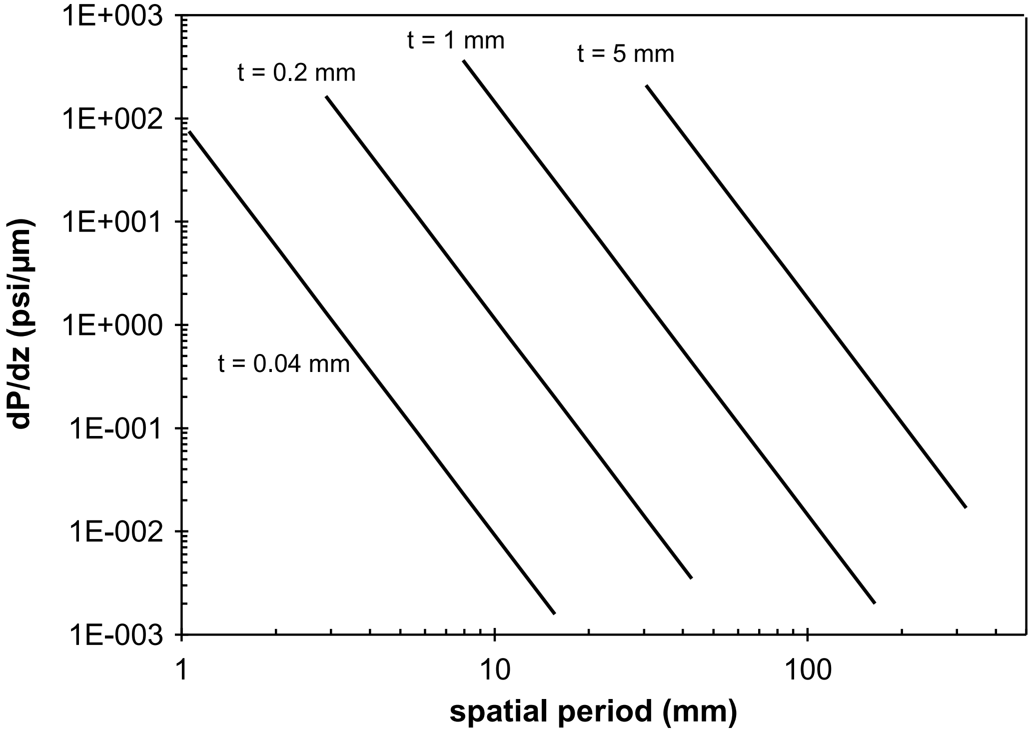


**Figure 5.** Bending stiffness for an aluminum polishing tool to sinusoidal ripples as a function of spatial period. The plot gives the local pressure variations under the tool in units of psi if it is run over 1 µm irregularities. Since the system is elastic, the effects of non-sinusoidal ripples can be determined using Fourier analysis.

The above analysis indicates that tools should be very thick, then they will have good smoothing properties over all spatial scales. There are two limitations to this model that must be considered. First of all, the above analysis only treats the bending stiffness of the membrane. The compliance of the grinding interface and of shear effects can become significant over small displacements or small spatial scales. Also, for working aspheric surfaces, the tool must have sufficient compliance or it will not fit the surface and will behave poorly.

## 3.1 MODELING MEMBRANE TOOLS

Modern design tools allow the membrane to be optimized for its application. First, the optician must select the size tools he wishes to use and the strokes that will be made by the machine. The tool design is then driven by two simple rules:

- the attachment of the grinding surface to the membrane should be as stiff as possible. This insures that the compliance to bending, which falls off as $L^4$,dominates.
- the membrane compliance is selected so it will take the aspheric shape with pressure variations that are less than the nominal polishing pressure.

A modal analysis was used to calculate the compliance required to fit the aspheric surface. First the amount of bending that would be required of the lap was calculated in terms of low order modes. Then, the modal stiffness for each of the low order bending modes was calculated for a nominal disk using finite element modeling. Having performed the FEM analysis once, the modal stiffness for each mode can be calculated for any disk by scaling. Coupling the bending requirement with the stiffness for the same mode gives a pressure variation for each mode that would result from this tool. These pressure variations are added to give the overall pressure that would be expected under the lap. The modal technique is illustrated in Figure 6.

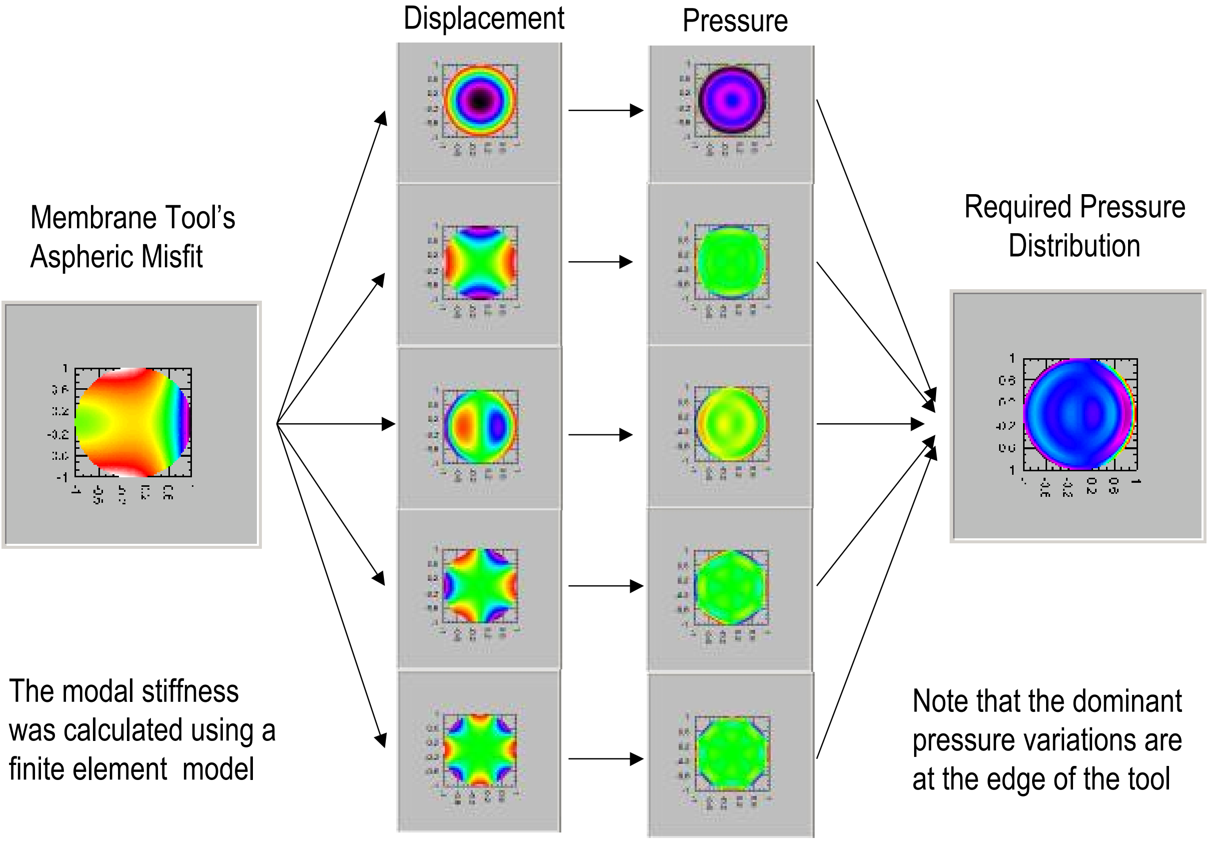
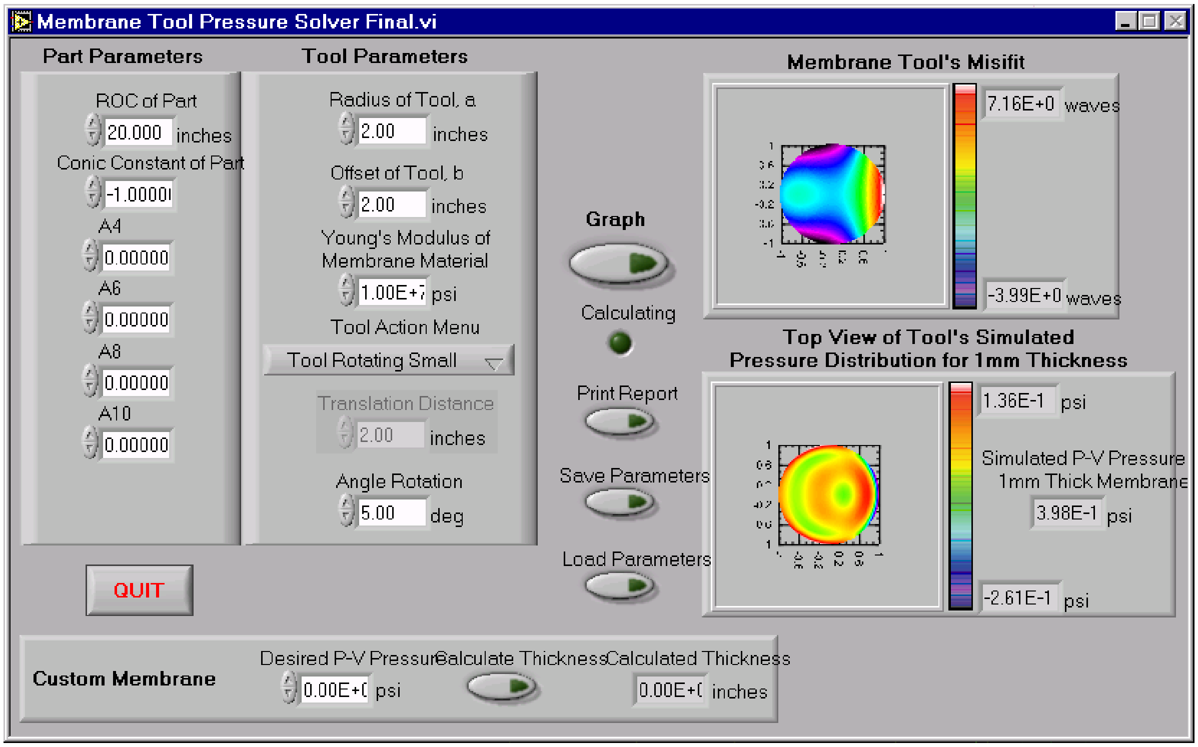


**Figure 6.** Illustration of modal analysis for determining pressure variation under the lap. The misfit of the lap is calculated for the particular lap and stroke in terms of low order Zernike polynomials. The bending stiffness for a thin plate was calculated for each mode. By coupling the two, a pressure map for each mode is calculated, then combined to give a net pressure map.

Note that sharp pressure variations occur at the edge of the tool. This is easily understood because the lap bending is always proportional to the moment in the plate. In order to bend the lap, a moment must be produced. The only way to make a moment near the edge is to have an upwards force next to a downward force. This tendency has been seen by other researchers as well.[6]

The above analysis was incorporated into a software package called "Toolmaker" that performs this analysis quietly, allowing the optician to select the properties of the tool he wishes to use. The software then selects the membrane thickness and shows the pressure map. The control screen for this program is shown in Fig. 7.


Membrane Tool Pressure Solver Final.vi

Part Parameters

ROC of Part: 20.000 inches
Conic Constant of Part: -1.00000
A4: 0.00000
A6: 0.00000
A8: 0.00000
A10: 0.00000

Tool Parameters

Radius of Tool, a: 2.00 inches
Offset of Tool, b: 2.00 inches
Young's Modulus of Membrane Material: 1.00E+7 psi
Tool Action Menu: Tool Rotating Small
Translation Distance: 2.00 inches
Angle Rotation: 5.00 deg

Membrane Tool's Misfit: 7.16E+0 waves; -3.99E+0 waves

Top View of Tool's Simulated Pressure Distribution for 1mm Thickness: 1.36E-1 psi; -2.61E-1 psi
Simulated P-V Pressure 1mm Thick Membrane: 3.98E-1 psi

Custom Membrane
Desired P-V Pressure: 0.00E+0 psi
Calculated Thickness: 0.00E+0 inches

**Figure 7.** Control screen for software that allows computer design of membranes.

## 3.2 EXPERIMENTAL RESULTS

Several tools of this type were constructed and applied to a highly aspheric surface. The membranes were made by hot vacuum forming plastic film onto the surfaces. The membranes were mounted to aluminum disks using closed cell neoprene foam. Metal tiles or polishing pads were bonded to the membrane for grinding and polishing. One of the tools is shown in Figure 8, and the use of this tool on a 40 cm f/0.5 surface is shown in Figure 9.

**Figure 8.** Composite tool with grinding tiles, plastic membrane, neoprene foam, and rigid backing plate.

**Figure 9.** The membrane tools were run using conventional polishing machines.

These tools have performed extremely well on very fast aspheric surfaces. A 40 cm test lens was made that had an *f*/0.5 convex surface with 450 µm departure from the best fit sphere. Figure 10 shows a Ronchigram of this lens after initial grinding. After 5 hours of work with the membrane lap, the sharp surface irregularities were smoothed out, as seen in Fig. 11.

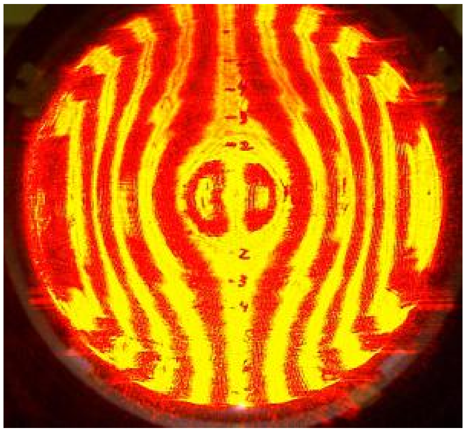


**Figure 10.** Initial Ronchigram from *f*/0.5 aspheric lens

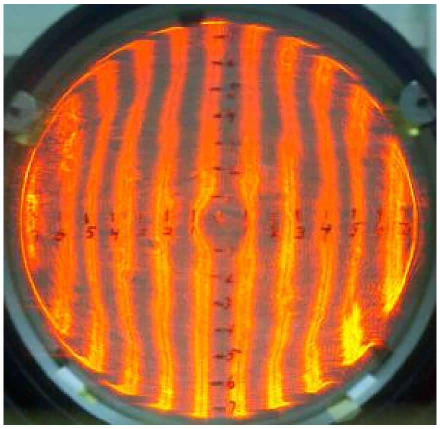


**Figure 11.** Measurement of the lens in Fig. 10 after 5 hours of work with the membrane tool.

## 4. FLEXIBLE RING TOOLS

The tools faced with membranes are extremely valuable, but the membrane stiffness limits their size to be much smaller than the size of the optic. For a very large tool with any stiffness, a new type of tool is required. We describe here a tool that uses annular rings as the stiffening element. These have large compliance to fit the aspheric shape, yet remain stiff over small scales to provide smoothing.

Coma is the largest bending mode required of a large lap, so it is desired to find a tool that has very low stiffness in this mode. This compliance is achieved using rings. For a single ring, the coma term is only tilt. There is a quadratic variation of this tilt for rings with different diameters, but any single ring sees only tilt. Also, power causes only piston, or shift along the axis, for the individual rings. A tool made up with nested concentric rings is naturally complaint to power and coma, as long as the rings are free to shift and tilt. This is illustrated in Figure 12.

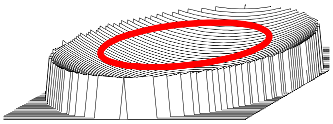
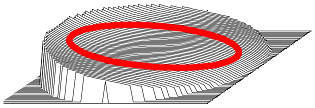
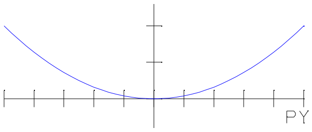
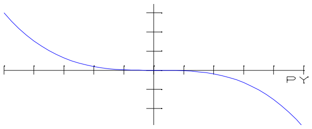
| | **Power** | **Coma** |
|---|---|---|
| Function | $a_2r^2$ | $a_{31}r^3\cos\theta$<br>$= a_{31}r^2x$ |
| for rings of constant r | ring shifts with $r^2$ dependence | ring tilts with $r^2$ dependence |
| Shape |  |  |
| Cross section |  |  |

**Figure 12.** The magic of rings. A single ring will always fit modes of power and coma. For power, the ring simply shifts axially and for coma, the ring tilts.

After allowing for power and coma, the dominant bending mode required of the ring is astigmatism, shown in Fig. 13. The compliance for astigmatism can be reduced using the geometry of the ring. When a ring bends in astigmatism, the dominant motion for any small section of the ring is torsion. Imagine bending a bicycle wheel (without the spokes). You could apply a twist at opposite sides and easily bend astigmatism. The local stiffness we desire comes from the bending stiffness of the section that is bent into the ring. Small scale stiffness can be optimized in the presence of global compliance to astigmatism if the ratio of the bending stiffness to the torsional stiffness is minimized. This occurs for sections that have a high aspect, like a band saw blade. The band saw blade has no torsional stiffness, so it is easily bent with large amounts of astigmatism. Yet, over short distances, the blade is quite stiff. (For real laps, the extreme thin dimension of the band saw blade is not practical, but it illustrates the concept.)

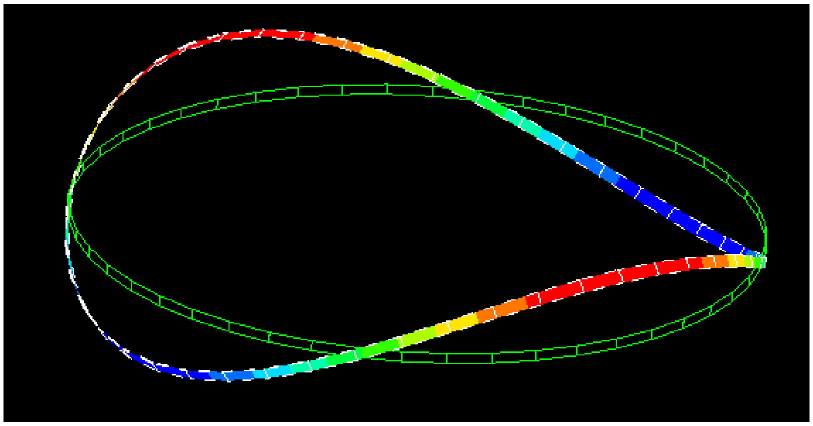


**Figure 13.** Each ring must bend in astigmatism to fit the aspheric surface.

A complete tool for grinding and polishing can be made as a set of nested rings, and the geometry of the tool must be designed and analyzed carefully. Figure 14 shows a tool layout for a 3-m tool designed to work a 4-m *f*/0.5 convex paraboloid. For this fast surface, the rings were made conical rather than cylindrical so that the polishing force is aligned to the desired bending axis of the section. This is illustrated in Figure 15.

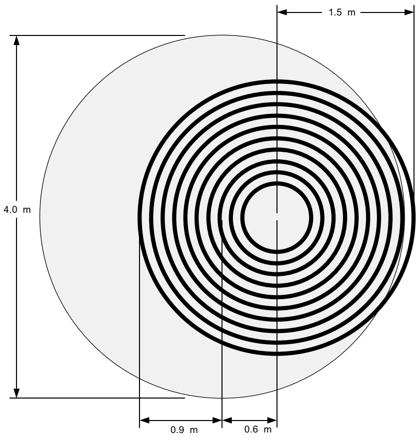


**Figure 14.** Layout for 3-m polishing tool using nested rings.

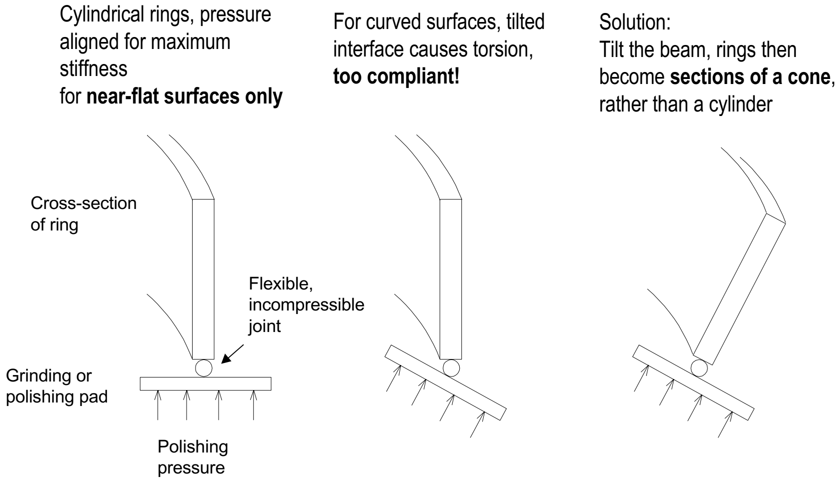


**Figure 15.** For steep surfaces, the rings must be made conical to maintain alignment of the surface normal to the desired bending axis of the ring section.

## 4.1 MODELING RING TOOLS

The ring tools were optimized using finite element modeling. This case is complex because each ring has two variables, the sectional height and width of the ring, and the membrane had only its thickness. The modal stiffness for representative rings was calculated using finite element modeling. Since we know the aspheric shape, we can use the stiffness to calculate the pressure variations that would be required to bend the ring into the desired shape. We require that the pressure variations around the ring are less than the polishing pressure and we can scale the solution accordingly.

This results in a class of solutions with different height and width for the section of the ring. This analysis was incorporated into the *Toolmaker* software to allow the optician to select the optimal ring geometry and analyze performance. The control screen for the software is shown in Fig. 16, including a graph showing the solution set for a particular ring.

The local stiffness of the tool is calculated using elastic beam theory. In the direction along the beam, the stiffness, as defined earlier, in units of polishing pressure variation per surface height variation with spatial period $L$ is

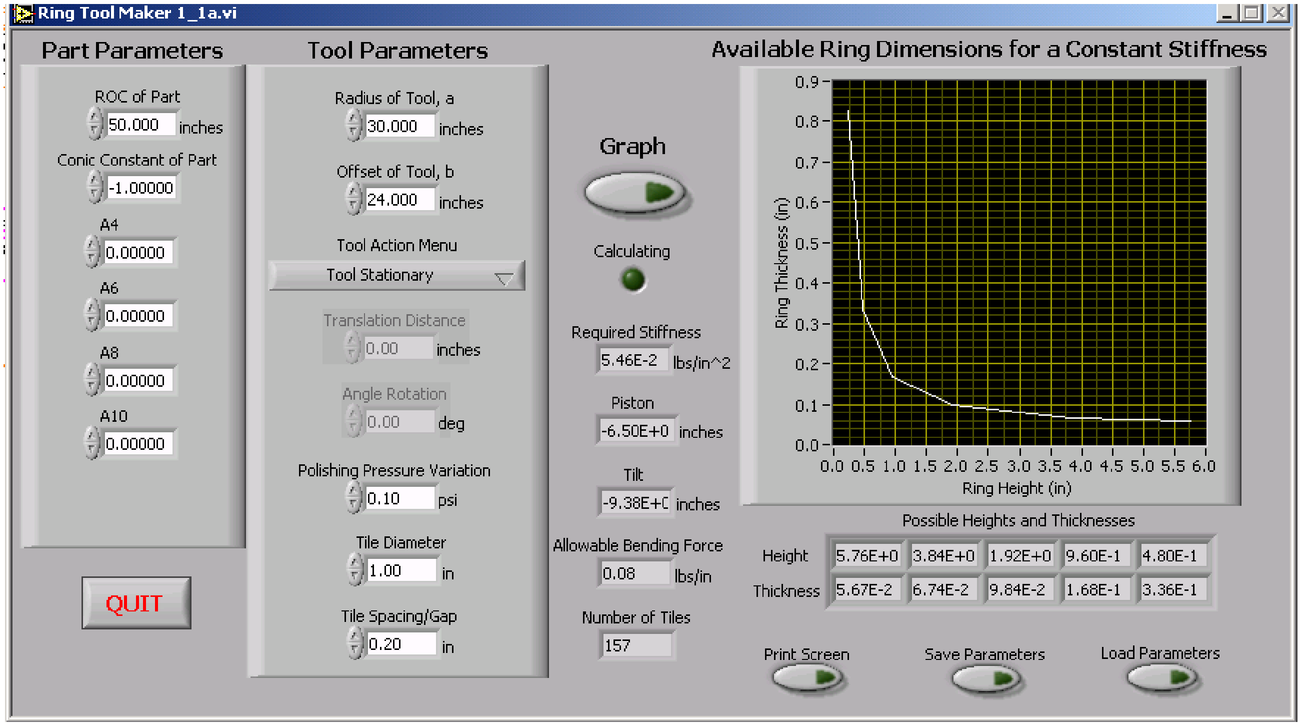
$$\frac{dP}{dz} = EI\left(\frac{2\pi}{L}\right)^4 \times \left(\frac{l}{A}\right)$$

where $I$ is the moment of inertia for the section

$E$ is the modulus of elasticitiy for the ring material

$A/l$ is the ratio of grinding area per length on the beam.

As before, this considers only bending compliance. It is important that the attachments to the polishing pads are stiff.



Part Parameters

ROC of Part 50.000 inches

Conic Constant of Part -1.00000

A4 0.00000

A6 0.00000

A8 0.00000

A10 0.00000

Tool Parameters

Radius of Tool, a 30.000 inches

Offset of Tool, b 24.000 inches

Tool Action Menu: Tool Stationary

Translation Distance 0.00 inches

Angle Rotation 0.00 deg

Polishing Pressure Variation 0.10 psi

Tile Diameter 1.00 in

Tile Spacing/Gap 0.20 in

Required Stiffness 5.46E-2 lbs/in^2

Piston -6.50E+0 inches

Tilt -9.38E+C inches

Allowable Bending Force 0.08 lbs/in

Number of Tiles 157

Possible Heights and Thicknesses

| | | | | | |
|---|---|---|---|---|---|
| Height | 5.76E+0 | 3.84E+0 | 1.92E+0 | 9.60E-1 | 4.80E-1 |
| Thickness | 5.67E-2 | 6.74E-2 | 9.84E-2 | 1.68E-1 | 3.36E-1 |

**Figure 16.** Software that calculates optimal geometry for rings for a grinding or polishing tool. The plot to the right shows the solution set for the cross sectional height and thickness of the ring. The rings are then chosen to use available stock.

## 4.2 ENGINEERING DESIGN FOR LAP WITH RINGS

The use of rings for providing local stiffness (for smoothing) and global compliance (to fit the asphere) is described above. The implementation of this concept requires careful design for the attachments of the ring to the drive spindle and of the ring to the polishing surface.

The rings must be able to “float” in position to compensate power and coma. Any section must also be able to rotate for the ring to bend in astigmatism. Yet we need to apply large forces to the ring to drive it in rotation and to provide the polishing pressure. The concept developed at the University of Arizona is shown in Fig. 17. We attach the ring using guide rods that are free to rotate at the ring. They are free to slide at the interface to the frame that holds the rings. The polishing force is maintained by placing weights on the guide rods. A drawing of a 3-m tool using this concept is shown in Fig. 18.

- Allow vertical motion using guide rods in linear bearings
- Allow rotation using spherical joint
- Constrain lateral motion
- Lateral force near polishing surface to minimize moments
- Supply drive force in circumferential direction
- Apply force using weights
- Designed for fabrication ease

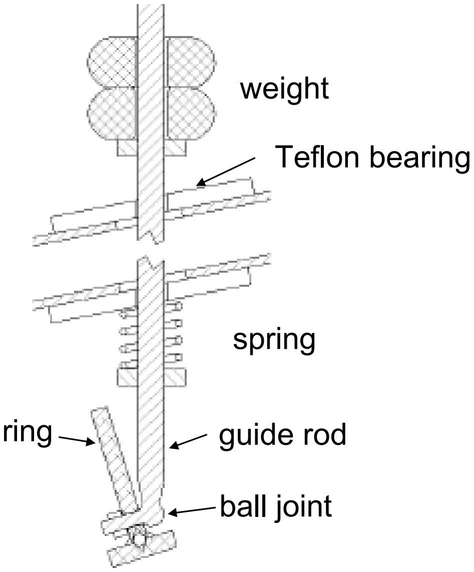


**Figure 17.** Attachment of the ring to the frame using guide rods that slip through bearings in the frame.

- Aluminum weldment
- Teflon bearings for guide rods
- Frame “floats” on rings using soft springs
- Drive torque and lateral forces taken at hub
- Lifting eyes are used to hoist frame, rings come with

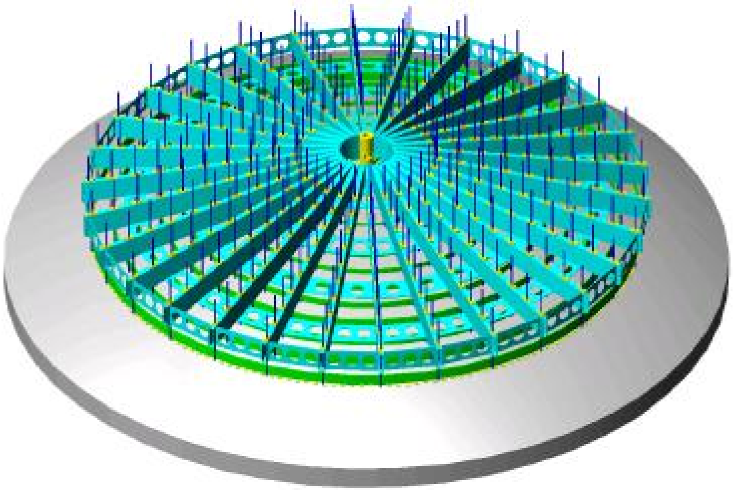


**Figure 18.** 3-m tool made from nested rings, supported by guide rods to a large frame.

The metal grinding pads are attached to the rings using ball bearings to provide a stiff connection, yet allow the pad to rotate. These are held in place using silicone adhesive. This geometry is shown in Fig. 19. For polishing, the metal pads are covered with polyurethane polishing pads or pitch.

- Use pads, small enough to always fit asphere
- Stiff attachment to ring
- Pivot on ball bearing
- Held on by silicone
- Grinding surface - metal
- Polishing surface - urethane
- Design for fabrication ease
- Maintenance is important

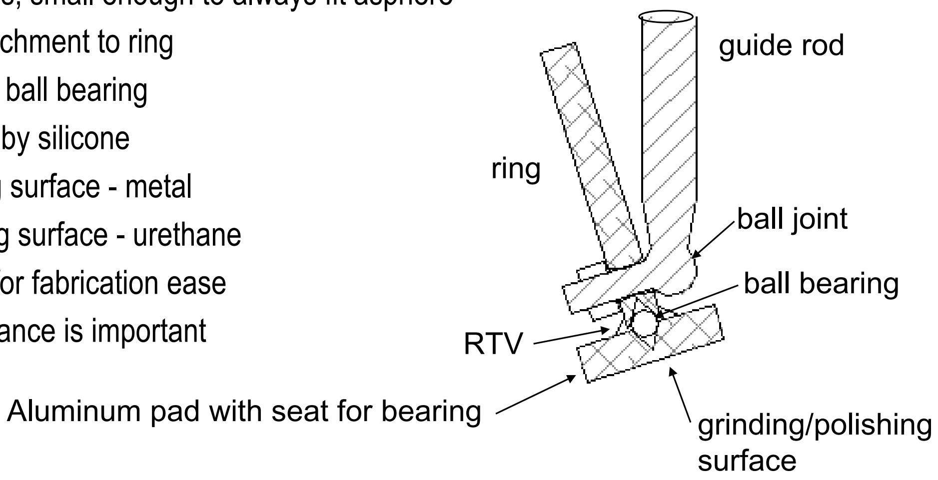


**Figure 19.** The grinding interface is provided by metal pads coupled to the rings with ball bearings.

## 4.3 EXPERIMENTAL RESULTS

A prototype ring tool was built and tested for manufacturing a 40 cm asphere with 450 µm departure from the best fit sphere. An engineering design of the tool is shown in Fig. 20 and the actual tool is shown operational in Fig. 21. The goal of this test was to run a large tool for hours over the part in order to get large removal without making large changes to the global shape. The data shown in Figures 21 and 22 show that the operation of this tool does work to smooth out zones, and it does not roll the edge even though it was driven well over the edge.

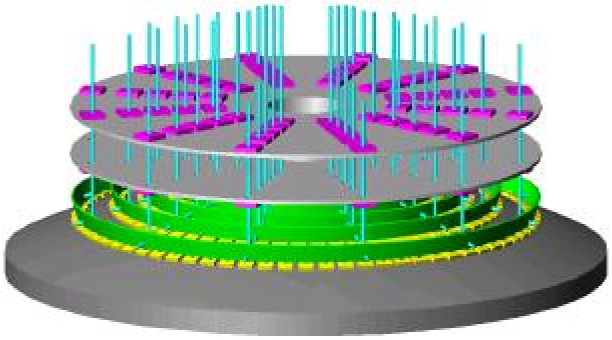


**Figure 20.** Engineering model for 30 cm ring tool.

**Figure 21.** Prototype ring tool in operation.

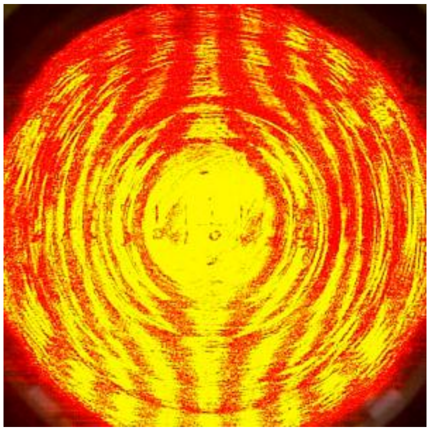


**Figure 22.** Ronchigram of $f/0.5$ lens after initial asphierization.

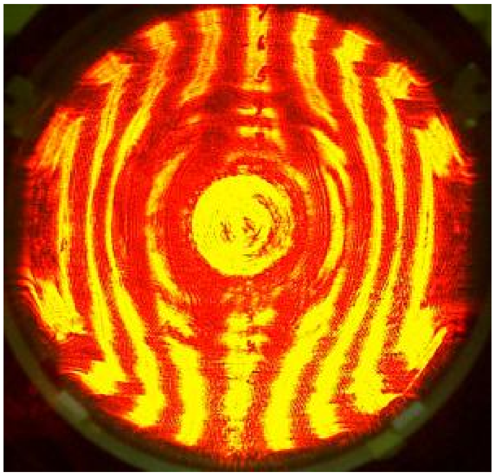


**Figure 23.** Ronchigram of $f/0.5$ lens after 4 hours of work with the 30 cm ring tool.

## 5. CONCLUSION

New tools for working steep aspheres are presented. Preliminary data indicate that these tools have excellent performance. We are now following up this work with other more quantitative studies.

## ACKNOWLEDGMENTS

Some of this work was funded by Composite Optics, Inc. in support of the FIRST project.

## REFERENCES

1. R. A. Jones, “Grinding and polishing with small tools under computer control,” Opt. Eng. **18**, 390-393 (1979).
2. D. Anderson and J. Burge, “Optical Fabrication,” Chapter 26 in *Handbook of Optical Engineering*, D. Malacara and B. J. Thompson, eds.,(Marcel Dekker, New York, 2001).
3. S. C. West, *et al.,* “Practical Design and Performance of the Stressed Lap Polishing Tool”, Applied Optics **33**, 8094 (1994).
4. J. H. Burge, “Simulation and optimization for a computer-controlled large-tool polisher,” OSA *Trends in Optics and Photonics Vol. 24, Fabrication and Testing of Aspheres,* J. S. Taylor, M. Piscotty, and A. Lindquist eds.(Optical Society of America, Washington, DC 1999).
5. H. M. Martin, *et al.*, “Polishing of a 6.5 m f/1.25 mirror for the first Magellan telescope”, in *Optical Fabrication and Testing*, R. Geyl and J. Maxwell, eds., Proc. SPIE **3739**, p. 47-55 (1999).
6. P. K. Mehta, R. E. Hufnagel, “Pressure distribution under flexible polishing tools. I - Conventional aspheric optics,” in *Advances in optical structure systems,* J A Breakwell, V L Genberg, G C Krumweide, eds., Proc. SPIE **1303**, 178-188 (1990).