

Contour Mode Deterministic Microgrinding

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ABSTRACT

The Center for Optics Manufacturing, along with its partners in the Consortium for the Deterministic Design, Manufacture and Assembly of Aspheric Optics, has recently completed (December, 1998) a three year, DARPA funded program to develop new manufacturing technology to produce axially symmetric, high departure aspheric optics. One result of the program was the development of a contour mode aspheric grinder and deterministic microgrinding process that repeatably produces aspheric optical surfaces in glass or IR materials with less than 1.0 wave p-v figure error, surface roughness of 100 Å rms, and less than 1 µm of sub-surface damage. Forty-millimeter diameter surfaces can be fabricated to these tolerances in less than 30 minutes from a rough blank. This paper will review the new machine and process manufacturing technologies that provide the capabilities outlined above. Details of the grinding process sequence are described. Results from grinding trials in a wide range of glass, crystalline and polycrystalline materials are reported. In addition, the results from demonstration parts fabricated for the Consortium partners in both glass and IR materials (FS, SLAM55, AMTIR, ZnSe, Silicon) will be shown.

Another DARPA funded consortia was formed to systematically identify and attack the manufacturing technology and cost drivers preventing the use of non-traditional optical shapes and materials in new capability optical sensors. The freeform grinding machine developed to meet these unique needs was recently completed and this paper reports on the machine design and the initial results from the grinder.

Keywords: deterministic microgrinding, glass grinding, contour grinding, aspheric and conformal optics fabrication

1. INTRODUCTION

1.1 Aspheric Optics

It is well known that aspheric lenses permit optical designs with fewer elements, resulting in decreased system weight, size, complexity, and cost, as well as increased transmissivity. For weapon and targeting

systems, these benefits translate into military advantages, such as increased range or speed or improved target acquisition. However, the lack of a cost-effective manufacturing technology for the fabrication of glass aspheres has been a significant barrier preventing the widespread use of aspheres in precision, visible optical systems. Existing fabrication techniques are costly because of long cycle times, high costs for capital equipment and tooling, and a lack of deterministic finishing techniques.

As a result of these issues, the Defense Advanced Research Projects Agency (DARPA) funded a program to develop, demonstrate, and deploy a cost-effective precision asphere design, fabrication, and assembly capability within the optics industry. Under this program, the Center for Optics Manufacturing (COM) at the University of Rochester led a consortium that has successfully developed the *NanotechO 150AG*, a cost effective aspheric grinder that can deterministically microgrind aspheres in brittle materials. The resulting ground surfaces can then be deterministically polished using the magnetorheological finishing (MRF) technique also pioneered at COM and commercialized by QED Technologies. A key objective of our program was to demonstrate a prototype, automated process to microgrind and polish precision aspheres at 1/10th the cost of current volume production processes. The consortium members included: Byelocorp Scientific, Eastman Kodak, Lockheed-Martin, Moore Tool/Moore Nanotechnology Systems, Opkor, OptiPro Systems and Raytheon Systems.

1.2 Conformal Optics

All projections for future military systems indicate that the trend toward higher performance optical solutions will continue to accelerate. As next generation weapon systems evolve, military prime contractors are finding direct conflicts between requirements for optical sensors and the need for weapons systems to have low observability, aerodynamic improvements, and increased optical performance. Attempting to mitigate these conflicts using traditional optical shapes (spherical lenses, flat windows) results in unacceptable compromises that make the use of traditional optical shapes completely inadequate for many next generation systems. A new

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class of optical shape is needed to meet these new requirements.

The new optical shapes are defined by the need to conform to the mechanical or aerodynamic requirements of the platform on which they reside. This class of optical shape has been named conformal optics. Conformal optical shapes include both axisymmetric and non-axisymmetric optical components and may have a combination of aspherical, spherical, cylindrical, conical, diffractive, plano, or ogive shapes. In some extreme cases, there may be no symmetry to the shape at all and these are called “freeform” shapes.

The combination of extreme accuracy requirements and difficult materials cause the optics required for next generation systems to be well beyond current fabrication capabilities – at any affordable cost. Another DARPA funded consortia was formed to systematically identify and attack the manufacturing technology and cost drivers preventing the use of non-traditional optical shapes and materials in new capability optical sensors. The grinding machine developed to meet these unique needs was recently completed and this paper reports on the machine design and the initial results from the grinder. In addition to COM, the consortia members included: Raytheon (several business units), Boeing, Rochester Photonics Corp., and the Optical Sciences Center, University of Arizona.

2. Asphere Grinding Machine Design and Results

2.1 Machine Design

The *Nanotech™ 150AG*, shown in Figure 1, is a high precision, cost-effective machine designed to grind rotationally symmetric aspheres with minimal mid-spatial frequency surface error. The grinder was designed and built by Moore Tool (Bridgeport, CT) under the direction of a COM-led Machine Technical Advisory Board. Moore Nanotechnology Systems, LLC (Keene, NH), an affiliate of Moore Tool Company was responsible for the final development of the aspheric grinder.

The *Nanotech™ 150AG* has two axes of linear motion mounted on a monolithic natural granite base. Both linear axes are fully constrained, oil hydrostatic, box way slides that use self-compensating bearing pads. There are two tool spindles, a ball bearing spindle for rough shaping operations (Parker Majestic) capable of speeds between 100 and 5,000 RPM and a choice of air bearing spindles for finish grinding operations (Westwind or Precision Instruments). The Westwind spindle is capable of speeds ranging between 5,000 and 40,000 RPM, the rough and finish grinding spindles are mounted to the

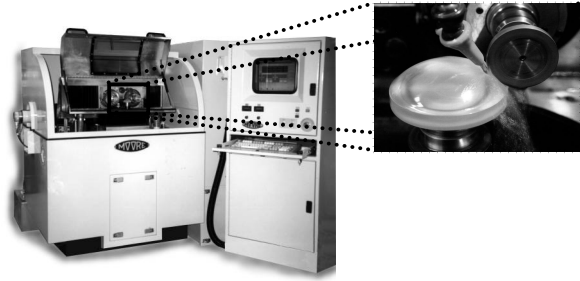


Figure 1: The *Nanotech™ 150AG*

X-axis, which traverses horizontally (350 mm travel). The work piece spindle (Precision Instruments) is also an air bearing design capable of speeds between 100 and 2,000 RPM. The work spindle is mounted to the vertical Z-axis (150 mm travel). The machine capacity allows for 150 mm diameter convex and concave components.

The *Nanotech™ 150AG* is controlled by an Aerotech PC-based NC control and has on-board instrumentation for dynamically measuring the effective grinding wheel diameter in order to compensate for wheel wear. In addition, an air bearing LVDT, mounted to the X-axis by the operator, can profile the ground optical surface before removing the part from the chuck. If necessary for extreme precision requirements, the data from the LVDT can be interfaced to a controller software routine to determine the tool path compensation needed for form error compensation.

2.2 Grinding Process

The standard grinding process developed for this machine is a two step sequence that uses a 10-20 μm diamond bronze bond tool for the roughing cut, and a 2-4 μm diamond resin bond tool for the finishing cut. Table 1 presents the typical process parameters used.

Table 1: Grinding tool specifications and process parameters

Tool	Bond	Manufacturer	Tool Speed (RPM)	Work Speed (RPM)	Feed rate (mm/min)	Depth of Cut (μm)
10/20	bronze	Scomac	7400	248	5	30
2/4	607c resin	Norton	12000	43	2	10 [†]

[†] Depth of cut was taken in three passes of 5, 2.5, 2.5 μm .

2.3 Contour Grinds of Spherical and Plano Surfaces

Several process development studies have been completed on a variety of materials. Because of the difficulties with metrology of large departure aspheres, the contour ground surfaces were either plano or spherical surfaces. Table 2 shows the p-v figure error and RMS roughness, averaged for several grinds in each material. All parts listed in Table 2

were 40-50 mm in diameter, 120 mm convex radius of curvature or plano. The contour grinding process consistently produces parts with figure error of 0.5 μm or less

Table 2: Figure and finish

Material	Average PV Figure error (μm) [†]	Average RMS roughness (\AA) [‡]
Fused Silica	0.4	158
ZnSe	0.5	99
Silicon	0.4	79
Amfir	0.4	158

[†] Zygo GPI interferometer

[‡] Zygo NewView 100, 20x mirau, areal roughness.

Most materials were ground to nearly final roughness specification, potentially eliminating the need for a polishing step. Measured subsurface damage was less than 1 μm for FS, the limit of the measuring technique. This correlates well with the p-v roughness measurement of 0.5 μm for this material.

In another study, the contour grinding process was used to grind 12 commonly used optical materials that represented a wide range of hardness and fracture toughness. The results demonstrate that the contour grind process is capable of producing parts to near-finished quality in a range of optical materials. Figure 2 shows the 12 materials included in the study and the results of the study.

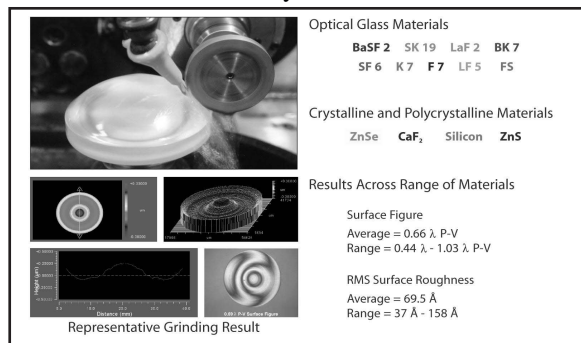


Figure 2: Glass, Crystalline and Polycrystalline Materials

The *Nanotech 150AG* was able to grind optical glasses to 50-100 \AA rms surface finish and hold figure error to less than 1 μm . The crystalline and polycrystalline materials were ground to approximately 200 \AA rms surface finish with figure error also less than 1 μm . Figure error was measured on the Zygo GPI interferometer and surface roughness data was taken on the Zygo NewView 100. All values in the table are the average measurements of five parts for each material type.

2.4 Contour Grinds of Aspheres

Two aspheres were ground to demonstrate the machine's performance. The first asphere, a 58.5 mm diameter SLAM-55 optical glass from Ohara, had an aspheric departure of 120 μm from the best fit sphere. The same two tool process was used as described

above, except that the tool used for the finish cut was a 10-20 μm resin tool (Norton 619c bond). Total grinding time was 25 minutes. Table 4 lists the final grinding results before polishing, and Figure 3 shows a plot of the figure error as measured by a Taylor Hobson Form Talysurf surface profilometer.

The second asphere, a 49.55 mm diameter zinc selenide optic, had an aspheric departure of 60 μm from the best fit sphere. The standard 2 tool process listed in Table 1 was used. The total grinding time was 49 minutes. This part had a longer grinding time because three finish cuts were taken using the 2-4 μm diamond wheel. Table 3 gives the final grinding results, and Figure 4 shows plots of the figure error.

Table 3: Aspheric results after grinding

Asphere	PV figure error (μm) [†]	RMS roughness (\AA) [‡]
SLAM-55	0.6	2153
ZnSe	0.6	111

[†] Figure obtained from Form Talysurf surface profilometer

[‡] Average of three places, Zygo NewView 100, 20x mirau

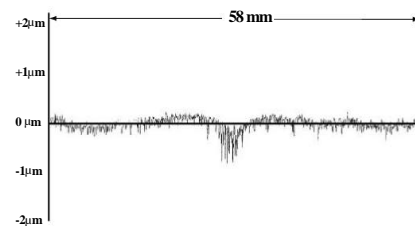


Figure 3: SLAM-55 Asphere Profile Error (unfiltered)

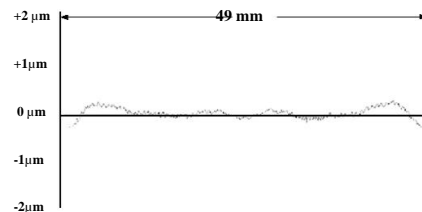


Figure 4: ZnSe Asphere Profile Error (unfiltered)

2.5 Contour Grinding Surface Errors

In addition to the well understood low and mid spatial frequency surface errors caused by problems such as machine alignment, periodic screw or spindle asymmetry and thermal variations, we have identified several other sources of errors that are inherent to the contour grinding process. Understanding and controlling these errors is critical to achieving sub-micron figure accuracy. Separating these errors from each other and identifying each error with an understandable source was one of the most difficult engineering challenges required to achieve the results described above. The understanding of surface errors created in 2 axis contour grinding developed during the process development of this machine led to design features in the conformal machine. A complete discussion of these errors will be the topic of another paper. A listing of the error types identified to date is provided below.

Table 4: Summary of Contour Grinding Surface Error Types

LOW SPATIAL FREQUENCY OR FIGURE ERROR SOURCES	MIDDLE/HIGH SPATIAL FREQUENCY ERRORS
<ul style="list-style-type: none"> Changes in volumetric removal 	<ul style="list-style-type: none"> Spiral marks
<ul style="list-style-type: none"> Tool wear 	<ul style="list-style-type: none"> Annular rings
	<ul style="list-style-type: none"> Chatter/ tool lobing

3. Conformal Grinding Machine Design and Results

3.1 Machine Design

The *Nanotech™ 500FG*, shown below, is designed to grind both axisymmetric and non-axisymmetric optical components and other shapes that may include a combination of aspherical, spherical, cylindrical, conical, diffractive, plano, or ogive shapes; or be freeform in materials ranging from optical glass and infrared materials, to non-ferrous metals, crystals, polymers and ceramics. The grinder was designed and built by Moore Nanotechnology Systems (Keene, NH) under the direction of a COM-led Machine Technical Advisory Board.

The computer numerically controlled, four-axis, ultra-precision machining system is capable of generating arbitrary conformal optical surface shapes within a 250 mm x 250 mm x 300 mm machining envelope. The machine has three linear motion axes and one rotary axis mounted on monolithic natural granite main base with natural granite risers to support the Z axis. All three linear axes use fully constrained, oil hydrostatic, box way slides. The horizontal work spindle is an air bearing design (Precision Instruments) capable of speeds between 100 - 2,000 RPM. The oil hydrostatic bearing grinding spindle (Moore Nanotechnology) is capable of speeds between 10,000 and 40,000 RPM. The grinding spindle is mounted horizontally on an air bearing rotary axis capable of a full 360 degrees of travel

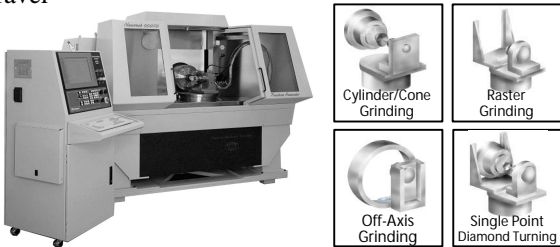


Figure 5: The *Nanotech™ 500FG* and grinding/turning configurations

In addition, an in-process, error compensation system using an air bearing LVDT can profile the ground optical surface before removing the part from the chuck. If necessary for extreme precision requirements, the data from the LVDT can be interfaced to a controller software routine to determine the tool path compensation needed for form error compensation.

3.2 Initial Acceptance Test Results

The conformal grinder recently completed acceptance testing trials at Moore Nanotechnology. The grinding process used was based on the knowledge gained from the experience with the asphere grinder. Table 5 shows the grinding tool specifications and process parameters.

Table 5: Grinding tool specifications and process parameters

Tool	Bond	Manufacturer	Tool Speed (RPM)	Work Speed (RPM)	Feed rate (mm/min)	Depth of Cut (μm)
2/4	607c resin	Norton	12000	43	2	10 [†]

[†] Depth of cut was taken in three passes of 5, 2.5, 2.5μm.

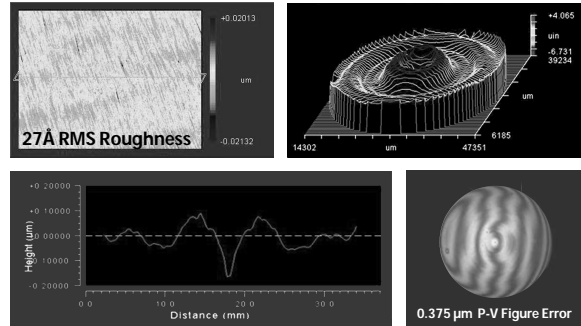


Figure 6: The initial results from the *Nanotech™ 500FG*; BaSF2 40 mm φ, 120mm radius sphere

SUMMARY

This paper reviewed recent work at the Center for Optics Manufacturing to develop a deterministic microgrinding capability for aspheric and conformal optical shapes. Average figure accuracy of 0.66 λ p-v was given for contour ground surfaces on a variety of materials for the *Nanotech™ 150AG* asphere grinder. Initial test results were shown for the *Nanotech™ 500FG* conformal optics grinder, indicating the ability to grind glass materials to under 0.5 λ p-v figure error.

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