

A Reprint from the

PROCEEDINGS



Volume 656

Contemporary Optical Instrument Design, Fabrication, and Testing

17-18 April 1986
Innsbruck, Austria

Diamond grinding of optical surfaces on aspheric lens molds

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Abstract

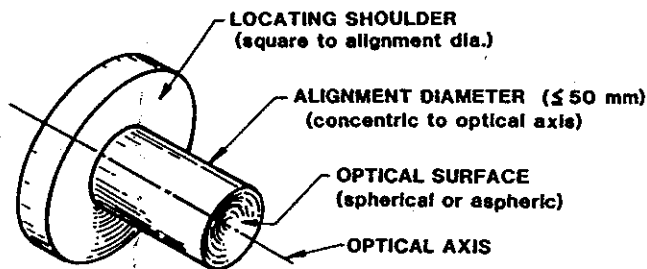
Through previous marketing surveys and discussions with many companies in 1984 and '85, it has become apparent that there is a growing need for a grinding machine capable of producing high quality, aspheric optical surfaces on various brittle materials that cannot be directly machined by single crystal diamond tools. Some of the materials of prime interest are ceramics and carbides, to be used as molds for plastic and glass lenses. Even though tool steel substrates with electroless nickel plating are being directly machined by single crystal diamond tools and used for injection molding of plastic lenses, the harder carbide and ceramic substrates have more desirable properties as molds for both plastic and glass lenses. Various applications of these lenses include use in:

- Cameras and Photocopiers
- Fiber Optic Connectors, and
- Pick-up Heads for Compact Disc Players for both audio and read only memory (CD-ROM) applications.

Upon closer evaluation of these applications, it is clear that a major portion of the lens mold market will be satisfied by the ability to grind aspheric surfaces up to a maximum diameter of 50mm. Also, to fulfill other requirements of these molds, a grinder must be capable of producing accurate alignment diameters and shoulders which are concentric and square to the optical axis of the aspheric surface. (see Figure 1.)

This paper will discuss the design of a Grinding Attachment for a standard turning lathe, which is being used for fabrication of the lens molds previously described. It focuses on grinding of a silicon carbide mold. The following key areas will be discussed in detail:

- Process Development
 - a. grinding wheel selection
 - b. wheel dressing
 - c. wheel setting
 - d. cutting parameters
- Restrictions/Limitations
- Accuracies Achieved
 - a. form error
 - b. surface finish



TYPICAL LENS MOLD
(concave)

Figure 1.

Introduction

Because of the high accuracy and high stiffness of our Ultra Precision-2000 Diamond Turning Lathe, we chose this machine as the basic system on which our grinding attachment would be used. The Ultra Precision-2000 is a two axis, CNC controlled lathe with a laser interferometer position feedback system. It has a T-base design with hydrostatic oil bearing slides and an air bearing spindle; and operates with a system resolution of 0.01 micrometer (0.4 microinch). (see Figure 2.) When used with single point natural diamond tools, it can machine optical components up to 300mm (12 inch) diameter with a maximum sag depth of 150mm (6 inch).

*This paper was part of a joint session with SPIE Conference 655, Optical System Design, Analysis, and Production for Advanced Technology Systems and appears in SPIE Proceedings Vol. 655 as Paper Number 655-51.

Figure 2.

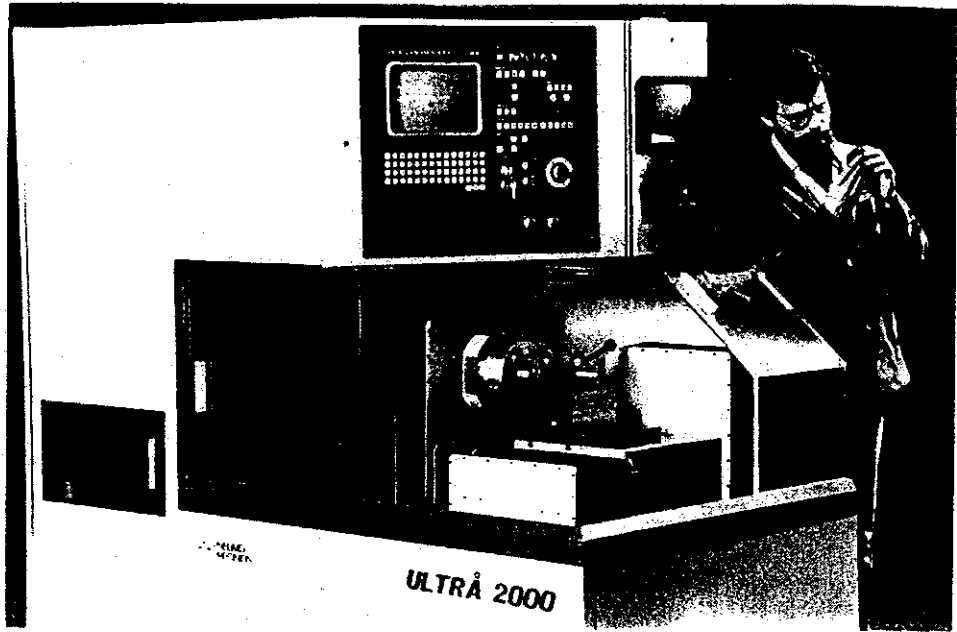
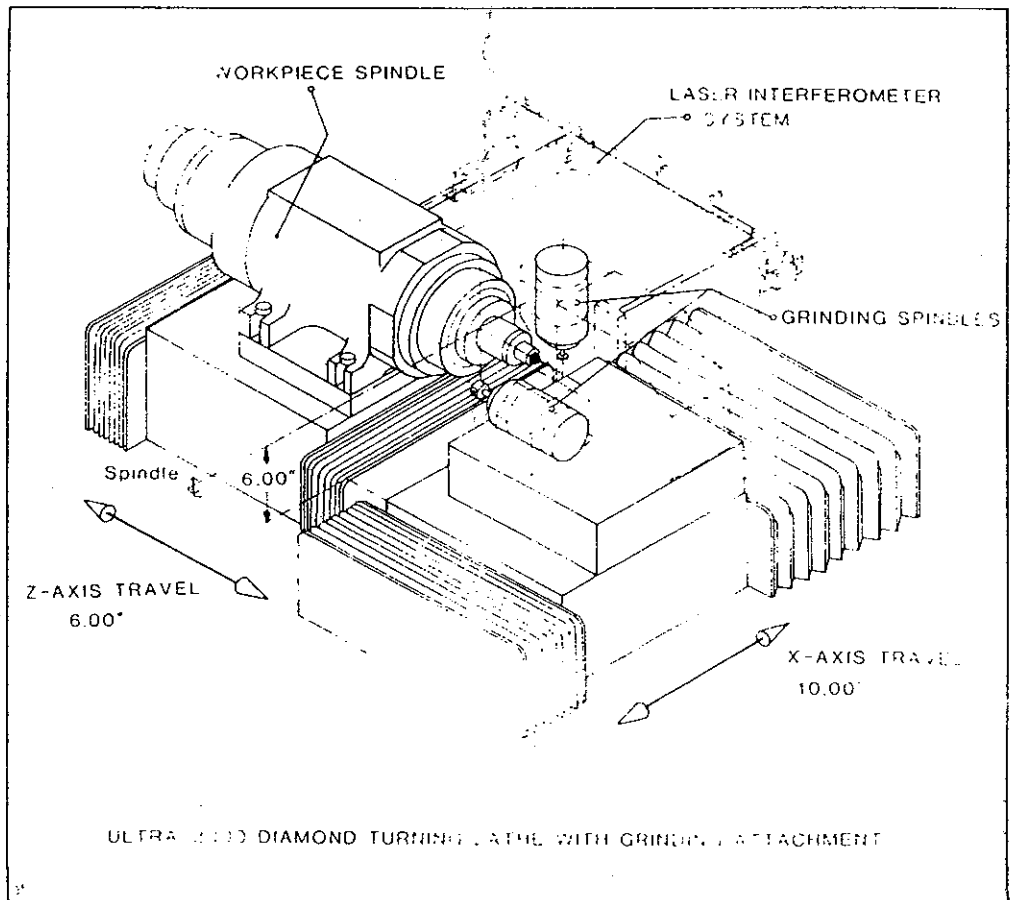


Figure 3.



The grinding attachment was subsequently designed using two high speed ball bearing grinding spindles which mount to the X axis slide in a special holding fixture as shown in Figure 3. These spindles operate through a variable speed range of 40,000 to 110,000 RPM and have the bearings lubricated via an air/oil mist system. One grinding spindle is mounted with its axis vertically perpendicular to the axis of the workpiece. This spindle is used for grinding the optical (aspheric) surface by moving both slides simultaneously via linear interpolation in the part program. The other spindle is mounted with the axis horizontally parallel to the axis of the workpiece. This spindle is used to grind alignment diameters and locating shoulders when required. All other peripheral equipment for the grinding system is mounted on a remote cart which is positioned behind the machine. This equipment includes the drive electronics for the grinding spindles, the coolant pumping system for temperature control of these spindles, and a completely separate coolant system to supply flood coolant to the grinding area.

The workpiece is mounted in a fixture that attaches to the air bearing workpiece spindle which has less than 0.1 micrometer (4 microinch) axial and radial runout. To assure rigidity in the mounting of this workpiece, most parts are clamped or pitched into the workholding fixture by their outside diameter. The workholding fixture is designed with a large flat face on the back which can be held by a vacuum chuck on the air bearing spindle. This mounting technique facilitates interim part testing and "on-machine" wheel dressing by permitting rapid removal and remounting of the fixture on the vacuum chuck. 3-jaw precision air chucks are also used for some applications.

Process Development

To achieve the best possible results, each workpiece requires a significant amount of process development to determine the best grinding parameters as well as the most efficient method of manufacturing. The process development discussed in this paper will concentrate on the information gathered through our previous grinding of optical (aspheric) surfaces on tungsten carbide and silicon carbide workpieces. Determining a satisfactory grinding process for these materials required a detailed analysis of several key areas, including:

- A. Diamond Grinding Wheel Selection
 - size
 - bond
 - grit (size and type)
 - concentration
 - mounting technique
- B. Wheel Dressing
 - rough forming
 - finish trueing
- C. Wheel Setting
 - horizontal centerline
 - vertical centerline
- D. Cutting Conditions
 - grinding spindle speed
 - workspindle speed
 - depth of cut
 - feedrate
 - type of coolant

A. Grinding Wheel Selection: To increase rigidity and reduce wheel wear, we chose a wheel with the largest outside diameter and the largest mandrel diameter that would still physically fit into the contour of the smallest diameter workpiece; with the steepest concave radius. The wheels were then mounted to the hardened tool steel mandrels with epoxy cement. After a significant amount of test grinding, we determined that the best finish and form accuracy were achieved with 1200 to 1800 grit resinoid bond diamond wheels. The wheels chosen used synthetic, blocky type diamond with 100% concentration.

B. Wheel Dressing: After the wheels were bonded to the mandrels, they were formed concentric to the mandrel via a low speed dressing operation in a normal shop lathe. To assure proper dynamic balance and minimize chatter during the grinding process, an accurate trueing technique was also necessary. To accomplish this, the mandrel (with bonded wheel) was mounted in the high speed grinding spindle and was finish dressed with an "on-machine" dressing attachment. This dressing attachment rotates a single crystal diamond nib "off-axis" of the workspindle centerline and is then traversed slowly into the rotating grinding wheel. This action forms a radius on the edge of the wheel and trues it to microinch tolerances. Typical wheel runout after finish dressing/truing was less than 0.5 micrometers (20 microinches) T.I.R.

C. Wheel Setting: To obtain final contour accuracy, it is mandatory for the centerline of the grinding wheel to be accurately established to the centerline of the work-spindle; both vertically and horizontally within 0.5 micrometer (20 microinches). (see Figure 4.) The horizontal position was established by mounting a dial indicator in a fixture plate on the air bearing spindle. This spindle was then rotated from side to side while indicating the outside edge of the grinding wheel. The X axis was moved accordingly to position the grinding wheel in the center of the swing of the indicator. Final adjustments were made to this position after evaluation of the interferogram of a spherically ground test part. Once this position was established, it did not need to be reset under normal conditions. To complete the wheel setting requirements, the vertical position of the wheel centerline (apex of the edge radius) was automatically established during the "on-machine" dressing operation mentioned previously.

WHEEL SETTING REQUIREMENTS

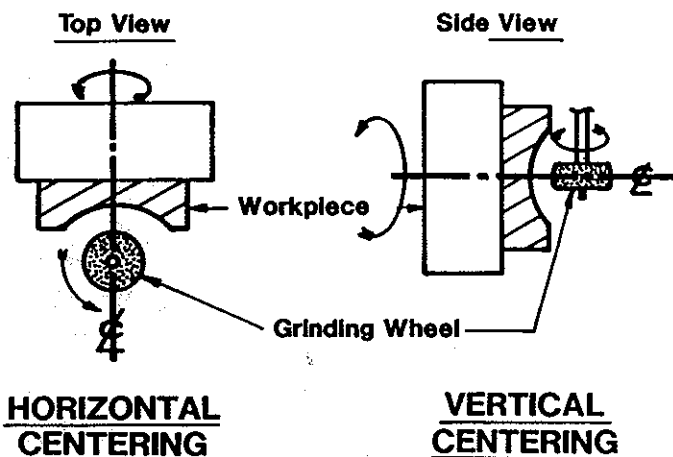


Figure 4.

D. Cutting Conditions: As generally recommended in diamond grinding applications, we maintained a nominal wheel speed between 1500 and 1800 meters per minute (5,000-6,000 surface feet/min.). Because of the various wheel diameters used, the speed of the grinding spindle was adjusted accordingly between 40,000 and 110,000 RPM. The workpiece spindle was normally run at 300 RPM. The parts were rough ground with a 2.0 to 5.0 micrometer (80-200 microinch) depth of cut and a feedrate of 2.5mm per minute (.1"/min.). On a finish pass, the typical depth of cut ranged from 0.5 to 1.0 micrometer (20-40 microinches) with a feedrate of approx. 1.2 millimeters per minute (.05"/min.). For grinding coolant, we used water soluble oil in a 20:1 mixture.

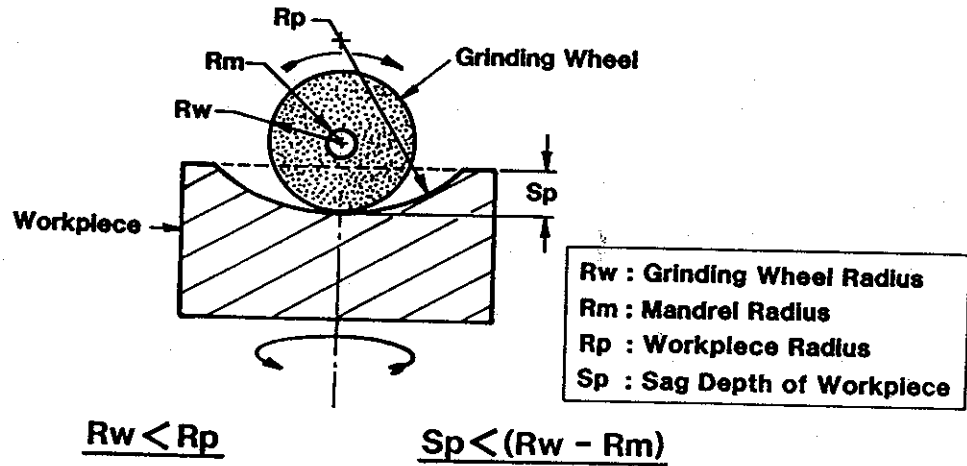
Restrictions

With this approach to grinding, there are several limitations that must also be discussed. Due to the variable frequency AC drive used on the grinding spindles, they can be satisfactorily operated through a speed range of 40,000 to 110,000 RPM. At the minimum grinding wheel speed of 40,000 RPM, the maximum size of a resinoid bond wheel is limited to 15mm diameter. (Larger sizes could exceed the manufacturer's maximum rated wheel speed and cause an unsafe condition). Naturally, this restriction in maximum wheel diameter limits the ability to grind total sag depth on some steep concave parts. The diameter of the mandrel must also be considered when calculating sag depth limitations. Two simple parameters should be used to determine the eligibility of a concave part for grinding by this approach. (see Figure 5.)

- A. The wheel radius (R_w) must be smaller than the part radius (R_p). On an aspheric curve, the wheel radius must also be smaller than any given radius dictated within the aspheric formula.
- B. The total sag depth of the concave part (S_p) must be less than the wheel radius (R_w) minus the radius of the mandrel (R_m).

RESTRICTIONS ON CONCAVE SURFACES

Figure 5.



Test Results

Upon implementation of the process development previously specified for carbide workpieces, we attained the following typical results by direct grinding parts of various sizes with convex or concave surfaces. Aspheres were manufactured with comparable accuracies to those produced on spheres, but due to ease in measurement, we will concentrate only on the test results of a sphere. As measured on a Rank Taylor Hobson - Form Talysurf measuring instrument 1,2, we achieved a total form error of 0.24 micrometers (9.6 microinches) on a 3.9mm diameter silicon carbide mold with a concave radius of 3.6mm. (see Figure 6.) Surface finish was also measured by the Form Talysurf and the results at various cutoffs are shown in Table 1.

TABLE 1

TABULATION OF SURFACE FINISH RESULTS (Direct Grinding of Silicon Carbide Mold)		
<u>CUTOFF</u>	<u>Ry/Rmax</u>	<u>Ra</u>
0.8mm (.030")	0.13um (5.2u")	0.02um (0.8u")
0.25mm (.010")	0.09um (3.6u")	0.014um (0.6u")
0.08mm (.003")	0.059um (2.4u")	0.009um (0.4u")

Additional testing with a Zygo Mark II interferometer showed the total form error to be approximately $\lambda/3 @ 6328\text{\AA}$, thus corroborating the previous results obtained on the Form Talysurf. (see Figure 7.)

**TAYLOR HOBSON - FORM TALYSURF
FORM / FINISH ANALYSIS**

F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand

Mode	Traverse Length	Reference	Ignore
UNFILTERED	3.7 mm	CONCAVE	0 %
PPI SAMPLE CONCAVE 3.6R			

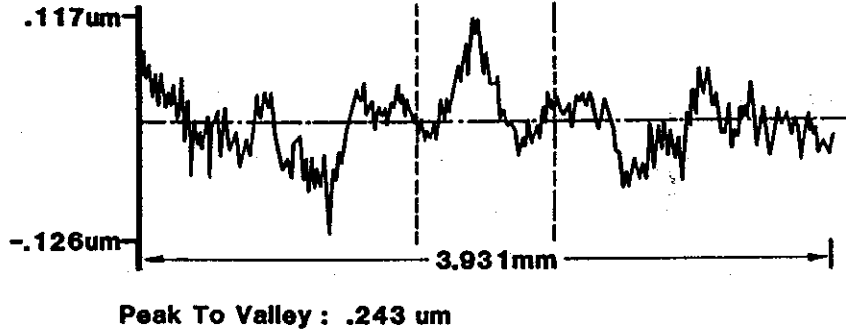
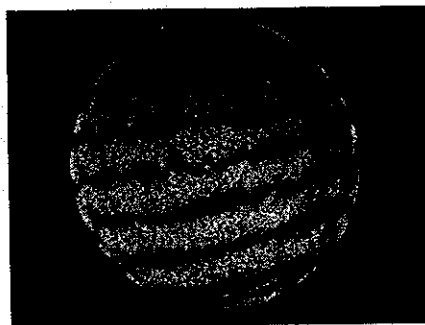


Figure 6.

**FIZEAU INTERFEROGRAM OF CONCAVE
SILICON CARBIDE MOLD (λ : 6328 Å)**

3.9mm Diameter / 3.6mm Concave Radius



**ZYGO Mark II Interferometer With
f /.75 Transmission Sphere**

Figure 7.

Conclusions

In the future, we plan to continue our grinding development on other workpiece materials as well as explore the future commercialization of flexible post polishing on aspheric surfaces. This work will be performed in conjunction with Rank Taylor Hobson, Leicester England. We are interested in expanding our process knowledge to cover a variety of additional materials of interest such as:

Glass (BK-7 & SF-1)
Ceramics
Molybdenum
Nickel
Tool Steels (Stavax)
Germanium
Silicon

To reduce the problems associated with wheel wear, we are also very interested in further process development with electroplated diamond wheels. As we progress with these future developments, we hope to achieve our goal of significantly expanding the production applications of ultra precision manufacturing.

Acknowledgements

The author wishes to thank Mr. Tom Dupell of Pneumo Precision and Mr. Hideki Ogawa of Rank Taylor Hobson KK for their assistance in providing some of the technical information for this paper.

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