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Comparison of Materials for Use in the Precision Grinding of Optical Components

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ABSTRACT

Precision grinding of optical components is becoming an accepted practice for rapidly and deterministically fabricating optical surfaces to final or near-final surface finish and figure. In this paper, a comparison of grinding techniques and materials is performed. Flat and spherical surfaces were ground in three different substrate materials: BK7 glass, chemical vapor deposited (CVD) silicon carbide ceramic, and sapphire. Spherical surfaces were used to determine the contouring capacity of the process, and flat surfaces were used for surface finish measurements. The recently developed Precitech Optimum 2800 diamond turning and grinding platform was used to grind surfaces in 40mm diameter substrates sapphire and silicon carbide substrates and 200 mm BK7 glass substrates using diamond grinding wheels. The results of this study compare the surface finish and figure for the three materials.

Keywords: ductile grinding, microgrinding, superabrasive grinding, silicon carbide, sapphire, BK7

2. INTRODUCTION

The ductile grinding of optical materials is a rapidly evolving process. Ductile regime grinding is the technology of grinding brittle materials at material removal rates and depth of cuts that allow for predominantly ductile removal of material as opposed to brittle fracture of the material. It has been hypothesized that for any material, if the material removal rate is sufficiently small, that the material removal will proceed by plastic flow as opposed to brittle fracture.¹ The transition from brittle fracture to ductile material removal occurs at the depth of cut whereby less energy is required to induce plastic flow or shear the material off the surface than to cause brittle fracture of the surface. The depth of cut at which this brittle-ductile transition occurs is often referred to as the critical depth of cut, d_c , and corresponds to the amount of material removed by the individual cutting particles.

This process relies heavily on several key equipment factors. The first is the availability of a high stiffness machining center. High machine stiffness is required to reduce errors caused by disturbance forces, high machining forces, and vibrations. Another factor is high slide resolution and feedback control which are required necessary to produce the low infeed rates necessary for ductile material removal.¹ Air bearing spindles combined with hydrostatic slides give the ductile grinding platform the smooth motion required to produce optical quality parts.

All materials were ground on the Ultraprecision Manufacturing Technology Center's (UMTC's) Optimum 2800 built by Precitech. The Optimum 2800 is a commercially available single point diamond turning and ductile grinding platform. The Optimum 2800 has a minimum airbearing stiffness of 60N/ μ m and a minimum slide stiffness of 33N/ μ m. Positioning is provided by a feedback controlled, optical-scale,

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positioning system with 10 nanometer resolution. The machine is built on a natural granite base and utilizes a pneumatic vibration isolation system. The hydrostatic oil bearing slideways are constructed in an offset "T" configuration where the X-axis (spindle) slide represents the cross-arm of the "T", and the Z-axis (tool holding) slide represents the stem of the "T". The grinding spindle is mounted vertically on the Z-axis of the system in a profiling configuration. Both the work spindle and the grinding spindle are air-bearing spindles.

The materials for this project were chosen to represent a sampling of the broad spectrum of materials available today to the optical or opto-mechanical engineer. BK7 glass was chosen because represent a conventional, transparent optical material, and because it readily lends itself to the ductile grinding process. Silicon Carbide was chosen due to its high specific stiffness (150mN/kg), structural stability, low density, and relatively large critical depth of cut ($d_c = 180$ nm as opposed to 6nm-10nm for fused silica and similar glasses). Silicon Carbide has applications in high energy optics, lens molds, and general lightweighted mirrors.^{1,2} Sapphire is a material of interest for the fabrication of transparent missile domes due to its high transmission, high strength, and thermal shock resistance. Sapphire also represents a very challenging material from a fabrication standpoint.^{3,4}

2. MACHINING SETUP

The conditions chosen for this study were based upon prior research. Parameter studies on each of the materials involved were not carried out as part of this experiment, however this experiment was carried out as an attempt to evaluate the results that could be expected on a day-to-day basis using previously established conditions. Also, this work was performed in order to gain experience using a new machine tool under a variety of conditions.

2.1 Grinding Wheel Setup

The setup of the grinding wheel is perhaps the most significant factor affecting the ability of the process to operate in the ductile regime. The grinding wheel must be "trued" so that all of the abrasive particles are at the same height. The truing process was performed by mounting a diamond tip on a simple fixture. This fixture was vacuum mounted to the work spindle normal to Z-axis of the grinding platform, and the tip was rotated about the edge of the wheel with the work spindle. The diamond tip was mounted such that it established a 5mm radius on the cutting surface. The diamond tip was programmed to cut into the grinding wheel in 2 micron steps. This operation was performed at process conditions including coolant. This process not only trues the wheel, it improves the grinding wheel balance and establishes the height of the grinding wheel such that it coincides with the work axis. The wheel run-out was less than one micron after the truing process.

The grinding wheel was then "dressed" to remove the bond material and expose the diamond cutting particles. The dressing process was carried out with an alumina dressing stick of the appropriate grit mounted on the work spindle. The work spindle was rotated at 500 RPM while the grinding wheel operated the process speed. The dressing stick was fed into the grinding wheel at a rate of 1mm/minute until 1cm of stick or more was removed.

Rough grinding was carried out with a 320 grit wheel of 50% diamond concentration. Finish grinding was performed using a four inch diameter 1800 grit wheel of 50% diamond concentration. Both wheels were of resin bond construction.

2.2 Machining Conditions

As stated previously, the machining conditions used in this experiment were based on previous work at the UMTC and at other facilities.^{2,3} Conditions were varied slightly to prevent synchronous error defects caused when the work spindle speed is a multiple of the grinding spindle speed. The feeds and speeds were varied depending on the critical depth of cut of the materials involved. The CVD silicon carbide and sapphire

blanks were rough ground on the ductile grinding platform from 40 mm blanks with no prior figuring. A ten inch radius of curvature, $f/6.7$, concave sphere was ground into these samples using a 360 grit diamond wheel. The 75mm BK7 substrate was rough ground prior to this study and only finish machining was required. The sapphire substrate consisted of a 28mm thick sapphire rod. The crystal orientation of the sapphire rod was unknown. Approximately, three liters per minute of coolant was used in all cases. Table 1 summarizes the grinding parameters used in this study.

The materials were attached to cylindrical mounts with wax. The cylindrical mounts were vacuum mounted to the chuck. The BK7 substrate was waxed to a fixture that supported the substrate in a 5mm ring around the edge of the part. The stiffness of this type of fixture was questioned during the evaluation, and it is possible that this fixture was not stiff enough for the process and contributed to errors in this part. Errors of this nature in the CVD silicon carbide substrate were reduced by eliminating this type of fixturing in favor of one that supported the entire optic.

The material was ground in successive passes in order to remove any subsurface damage created during roughing and during previous grinding passes. The sapphire sample had a slight amount of run-out (10-20 microns) when mounted on the grinding platform for the finish passes. Most of this run-out was left in the substrate after grinding, indicating that little material was actually removed from the substrate. The surface finish was improved dramatically during the finishing process. Possibly, more grinding passes at smaller cutting depths would have improved the surface figure and finish of this substrate, or the use of a slightly courser grinding wheel might also have led to some improvement.

Table 1. Grinding parameters for material survey.

Substrate	Silicon Carbide	Sapphire	BK7
Substrate Diameter	40mm	40mm	75mm
Sag of Sphere	0.9mm ($f/6.7$)	0.9mm ($f/6.7$)	3.2mm ($f/3$)
Roughing Wheel Geometry	75mm Diameter, 360 Grit, 10mm edge radius, Resin Bond	75mm Diameter, 360 Grit, 10mm edge radius, Resin Bond	75mm Diameter, 360 Grit, 10mm edge radius, Resin Bond
Roughing Parameters	6000 RPM Wheel Speed, 10 μ m/pass, 10mm/min	4000 RPM Wheel Speed, 5 μ m/pass, 5mm/min	6000 RPM Wheel Speed, 10 μ m/pass, 10mm/min
Finishing Wheel Geometry	100mm Diameter, 1800 Grit, 5mm edge radius, Resin Bond	75mm Diameter, 1800 Grit, 10mm edge radius, Resin Bond	100mm Diameter, 1800 Grit, 5mm edge radius, Resin Bond
Finishing Infeed and Crossfeed	6000 RPM Wheel Speed 5 μ m, 5mm/min(4 passes) 2 μ m, 2mm/min(4 passes) 1 μ m, 2mm/min(4 passes) .5 μ m, 1mm/min(2)	4000 RPM Wheel Speed 2 μ m, 2mm/min(4 passes) 1 μ m, 1mm/min(4 passes) .5 μ m, 1mm/min(4 passes) .1/0 μ m 1mm/min(4+)	7000 RPM Wheel Speed 5 μ m, 5mm/min (4 passes) 2 μ m, 2mm/min (4 passes) 1 μ m, 2mm/min (4 passes) 0.5 μ m 1mm/min (1 pass)
Workpiece RPM	231	186	231
Coolant	Challenge 300/Water; 1/30 dilution, 3.5 liters/min.	Challenge 300/Water; 1/30 dilution 3.5 liters/min.	Challenge 300/Water; 1/30 dilution, 3.5 liters/min.

3. RESULTS

3.1 Microstructure

Examining the microstructure of the finished material provides insight as to the material removal mechanisms involved in generating the surface. Nomarski microscopic photographs were taken of the three

materials as an aid to understanding this process. Figure 1 shows the surface topography of the silicon carbide sample at 500X magnification. The grooves in the photograph represent the areas where material was removed by the diamond particles in the grinding wheel acting in a ductile mode. Although brittle fracture sites are also visible, it appears that the majority of the material was removed by ductile shearing.

Figure 2 shows the surface of the sapphire sample. This surface shows some ductile material removal and some brittle fracture at 250X magnification. In the sapphire sample, slightly more ductile material removal than brittle material removal is evident. However, this distribution was not uniform over the surface of the sample. Most of the surface of the sample exhibited equal amounts of brittle and ductile material removal. Also, the surface had four distinct circular bands of material with more ductile than brittle material removed. The variation in the surface was likely due to the run-out in the surface which causes machine flexures and variations in the depth of cut.

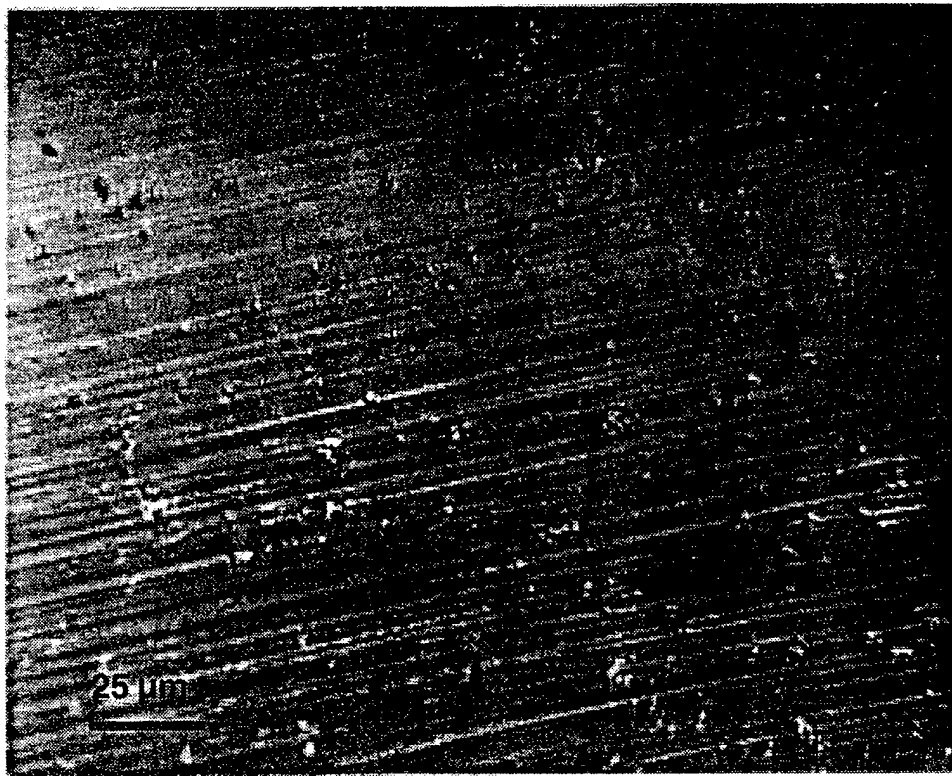


Figure 1: Nomarski micrograph of silicon carbide surface 500X objective

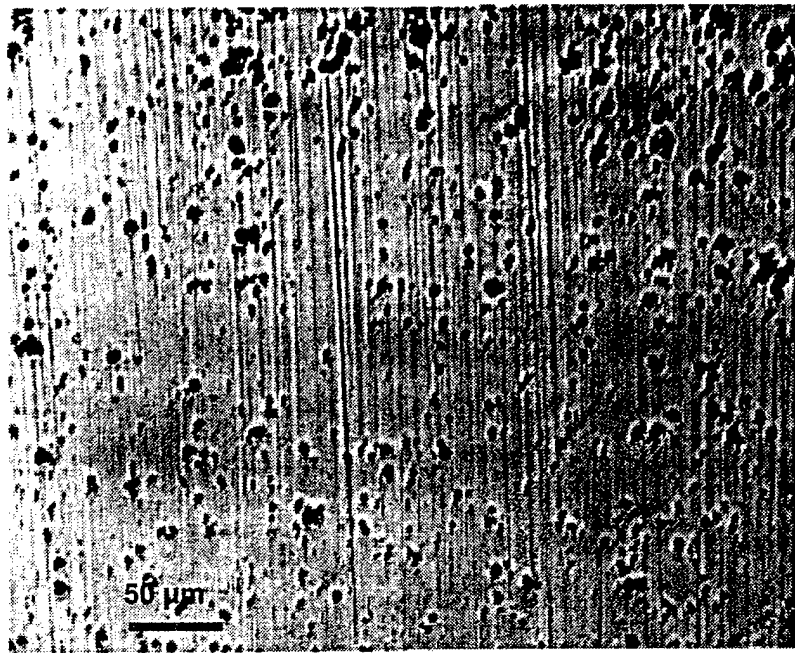


Figure 2: Nomarski micrograph of Sapphire Surface 200X objective.

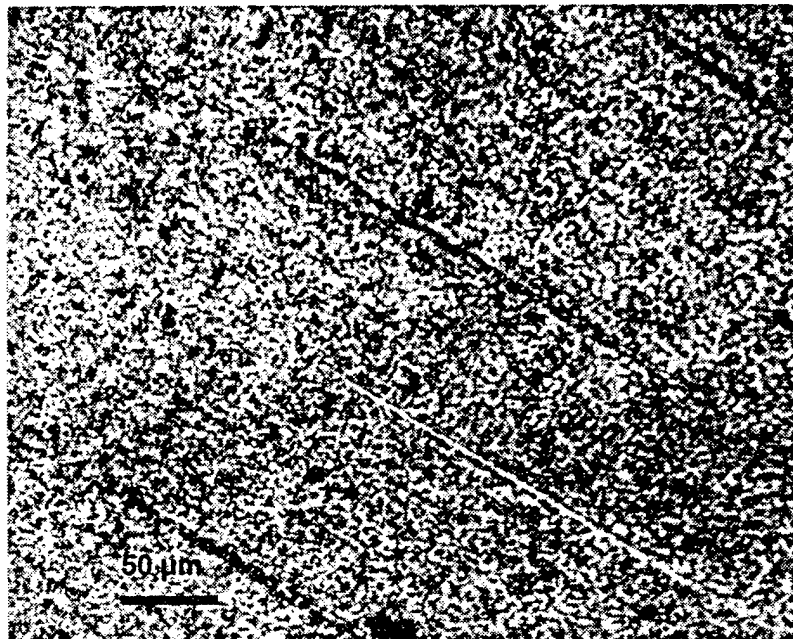


Figure 3: Nomarski micrograph of BK7 Glass 200X.

Figure 3 shows the BK7 surface topography. This surface appeared to be a very specular surface to the eye, however the microscope revealed porous or dimpled features. The pores on the surface were not jagged but appeared very small and smooth. This type of surface could result from damage created in early grinding passes that was not totally removed by finishing. The surface structure resulting from grinding BK7 deserves further investigation, and will be improved with refinements in the grinding process.

3.2 Surface Finish

The surface finish of the samples was measured by a Chapman MP2000 optical profilometer. Five 1mm scans were made at various locations on the surface and averaged to arrive at the values in Table 2. The bandwidth on the data is 1-200 micrometers. The 200 micrometer filter was used so that tilt and long wavelength waviness in the surface was removed. Any features from the grinding process remain and will be reflected in the data. A polished reference flat used for testing surface flatness was included with these results for relative comparison.

Table 2: Surface Roughness Data

Material	Polished Reference Flat	BK7 Glass	CVD Silicon Carbide	Sapphire
Surface Roughness Ra 1-200 μm , Å AVG. (standard deviation)	32.2 (1.2)	236.4 (33.1)	95.94 (16.9)	682.1 (79.0)
Surface Roughness Rq 1-200 μm , Å (standard deviation)	39.8 (1.1)	299.46 (38.2)	130.26 (23.1)	928.1 (90.48)

3.3 Surface Figure

The surface figure of the three samples was evaluated using a BRO (Breault Research Organization) phase shifting interferometer operating at 632.8 nanometers. The results of the interferometry are represented by the surface maps in Figure 4 and Figure 5. The silicon carbide sample achieved a 0.432 wave peak-to-valley and 0.074 waves RMS surface figure. The BK7 glass measured 0.69 waves peak-to-valley and 0.133 waves RMS. A significant amount of the figure error in the BK7 surface was due to fixturing as discussed in section 2.2. The silicon carbide sample experienced a similar error before it was fully supported on an aluminum flat.

The silicon carbide surface had a significant depression in the center of the surface where the toolpath ended. This error was reduced by eliminating any dwell time at the center of the part, but was not eliminated entirely. The width of the defect at the center of the part corresponds to the width of the grinding wheel contacting the surface. Since the error is very repeatable, a simple way to remove this error is to program a compensating path in the numerical controller. The same error was present in the BK7 surface also.

The sapphire sample was not of sufficient surface quality to measure interferometrically. This surface was sufficiently reflective to return light to the interferometer; however the surface appeared to be composed of many smaller surfaces reflecting light back into the interferometer, each with its own individual fringe pattern. The amount of run-out (10-20 microns) in the sapphire substrate also caused major problems with this surface. The run-out in the surface appeared to be a source of vibration and prevented the finishing process to proceed due to excessive depths of cut. This surface could be improved by a more thorough parameter study into the ductile grinding parameters of sapphire.

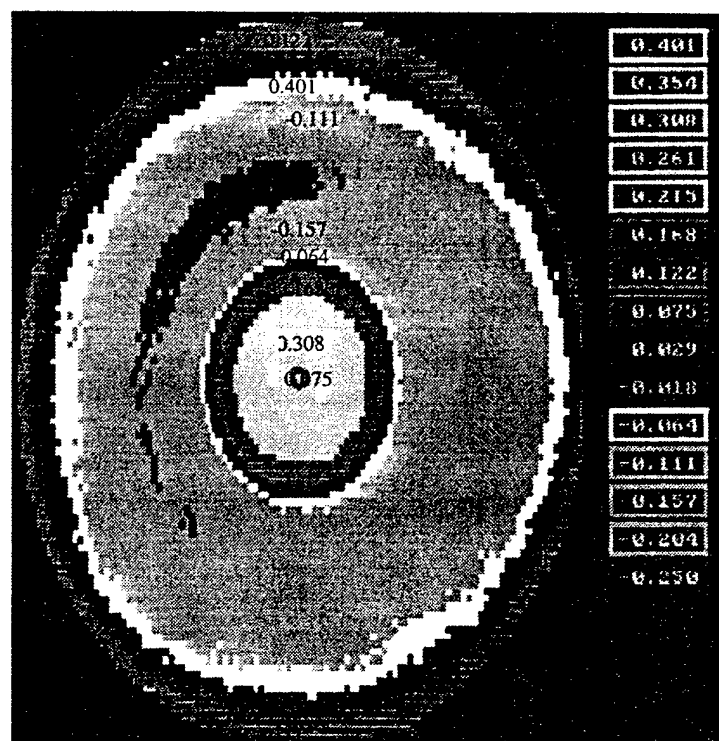


Figure 4: Surface map of BK7 $f/3$ sphere figure. Numbers are waves of 632.8nm. 0.69 total waves peak-to-valley, 0.133 waves rms.

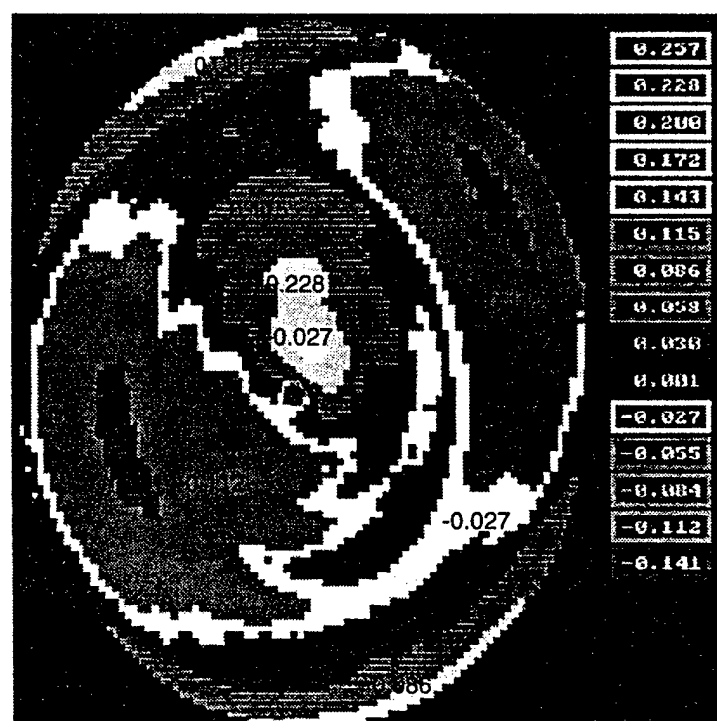


Figure 5: Surface map of $f/6.7$ CVD SiC sphere figure. Numbers are waves of 632.8. 0.43 waves total peak-to-valley, 0.074 waves rms.

4. SUMMARY

The evaluation of a new grinding platform and determination of typical results were the major reasons for this work. The Optimum 2800 proved to be a very capable and versatile platform. Surface figures of 0.7 waves peak-to-valley were produced in BK7 and 0.4 waves peak-to-valley were produced in CVD silicon carbide. The surface finishes produced in this study are of a high quality with 130Å RMS surfaces produced in silicon carbide, 299Å RMS in BK7, and 928Å RMS in Sapphire.

These surfaces were ground to very good accuracy with obvious areas for improvement in figure, one of the which is in the part fixturing. Materials fabricated by the ductile grinding process require good support. Also, it is necessary that no part run-out remain in the part during the finishing process or cutting cannot complete properly.

The ductile grinding process is a deterministic process capable of providing low cost aspheric components. Spherical surfaces were manufactured during this study only because of ease in testing. Once a deterministic process such as ductile grinding is characterized and qualified, it can produce aspheric optics as readily as spheres.

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