CONF-950793--39

UCRL-JC-121658
PREPRINT

Performance Evaluation of Bound Diamond Ring Tools

M. A. Piscotty
J. S. Taylor
K. L. Blaedel

This paper was prepared for submittal to the
SPIE The International Society for
Optical Egineering 40th Annual Meeting
San Diego, CA
July 9-14, 1995

July 14, 1995

Lawrence Livermore National Laboratory

MASTER

Performance Evaluation of Bound Diamond Ring Tools*

by

Mark A. Piscotty, John S. Taylor, Kenneth L. Blaedel
(Lawrence Livermore National Laboratory)

All authors are at Lawrence Livermore National Laboratory
P.O. Box 808, L-537
Livermore, CA 94551

Abstract

LLNL is collaborating with the Center for Optics Manufacturing (COM) and the American Precision Optics Manufacturers Association (APOMA) to optimize bound diamond ring tools for the spherical generation of high quality optical surfaces. An important element of this work is establishing an experimentally-verified link between tooling properties and workpiece quality indicators such as roughness, subsurface damage and removal rate. In this paper, we report on a standardized methodology for assessing ring tool performance and its preliminary application to a set of commercially-available wheels. Our goals are to 1) assist optics manufacturers (users of the ring tools) in evaluating tools and in assessing their applicability for a given operation, and 2) provide performance feedback to wheel manufacturers to help optimize tooling for the optics industry. Our paper includes measurements of wheel performance for three 2-4 micron diamond bronze-bond wheels that were supplied by different manufacturers to nominally-identical specifications. Preliminary data suggests that the difference in performance levels among the wheels were small.

Keywords: Ring tool, grinding, spherical generation, grinding wheel characterization, grinding wheel, fixed abrasive grinding, optical fabrication, diamond abrasives

Introduction

Industrial interest in using bound diamond ring tools instead of loose-abrasive processing for fine grinding is growing due to the improved flexibility for small and moderate-sized orders of custom optics, minimization of washing steps, better shape control, and potentially lower levels of roughness and subsurface damage. Hesitancy to make this switch to fixed-abrasives may stem from several sources, but is partially due to the lack of commercially-available, well-characterized ring tools that provide repeatable results, either within a given tool, or from tool-to-tool. Because of the relatively small market segment represented by fine grinding, wheel manufacturers have not pursued significant development efforts for fine diamond wheels, and often extrapolate from their production methods for coarse wheels to fine diamond powders.

LLNL and the Center for Optics Manufacturing are collaborating in developing the methodology for grinding high quality surfaces on brittle materials using bound diamond wheels. A key aspect of this work involves joining with optics and wheel manufacturers to develop tooling that is optimized for the final grinding operation. The specific

---

* This work was performed under the auspices of the U. S. Dept. of Energy by LLNL under contract No. W-7405-Eng-48.

performance requirements for the tools will vary among the optics industry, depending, for example, on whether a 2-step or 3-step grinding process is used. For the scope of this study, we are focusing on wheels for producing surfaces with roughness values of the order of 100 Å RMS and about 1 μm of subsurface damage.

Our long-term goal in developing grinding wheels will involve the design of the wheel, e.g. bond properties, based on the specification of the work material, grinding conditions, and the desired level of performance. However, attempts to associate wheel properties with performance indicators, such as surface roughness, have for the most part not been successful. This may be due to the lack of measurements of appropriate wheel properties and a lack of good performance characterizations. Clearly a testing procedure, that associates performance with wheel type, is an essential element in identifying optimal wheel properties.

Although grinding wheel characterization studies for coarse wheels have been conducted in the past[1, 2, 3, 4] characterization of ring tools for fine grinding have not been well developed. We have developed a series of performance tests designed to evaluate fine diamond ring tools for grinding glass optics. These tests incorporate ring tool, workpiece and grinding process evaluations to allow objective characterization of ring tools for grinding glass optics. Among the measurements are bond property measurements such as bond hardness and porosity, dimensional accuracy, grinding force measurements, wear ratio measurements, part quality such as surface roughness and subsurface damage and repeatability measurements. Our goals are to develop a ring tool evaluation procedure which will assist optics manufacturers in evaluating tools and assessing their applicability for a given operation and will provide performance feedback to the ring tool manufacturers to help optimize tools for the optics industry. This paper discusses our plan to conduct performance evaluations of bound diamond ring tools and will report on a few preliminary results from a partial evaluation conducted on three bronze bond fine diamond ring tools.

Experimental Platform and Ring Tool Generation

Our performance evaluation tests are conducted on a stiff, CNC Moore T-base diamond turning lathe which has been converted into a spherical generator. Figure 1 is a photograph of our generator and shown are a Westwind air-bearing high-speed grinding spindle and a Pneumo air-bearing workpiece spindle. The grinding spindle is mounted on a rotary table on the x-slide and the workpiece spindle is mounted on the z-carriage. The measured loop stiffness between the grinding spindle nose and the workpiece spindle face is 35 N/μm and position feedback for the x and z slides is provided by distance measuring interferometers with 25 nm resolution. Our goal is to employ a high quality grinding platform in order to minimize machine tool effects in assessing ring tool performance.

The geometry of the ring tool generation is well described by Karow[5], Storz[6] and Zschommler[7]. A close up of the grinding zone is shown in Figure 2 and in this view, a ring tool is shown in grinding position with a 40 mm diameter BK7 test workpiece. The in-feed angle at which the ring tool approaches the workpiece dictates the radius-of-curvature generated on the glass workpiece as

$$R = \frac{D}{2\sin(\phi)} \qquad \text{Eq. 1}$$

feed rates, depths-of-cut and spindle speeds were held constant throughout the grinding evaluation and they are shown in Table 2.

Table 2 - Test conditions for the initial experimental tests.

Ring Tool	Grit Size (μm)	In-Feed Rate (μm/min)	Depth-of-cut (μm)	Grinding Spindle Speed (rpm)	Workpiece Spindle Speed (rpm)
Coarse	75	2000	200	15000	180
Medium	10 - 20	50	50	15000	180
Fine	2 - 4	7	24	15000	180

An identical series of grinding tests were conducted for each of the three ring tools and the corresponding data for each wheel were measured and recorded. The grinding series is shown in Table 3. All three wheels were trued and dressed prior to the grinding tests.

Table 3 - Test evaluation grinding series followed in this study for each of the three fine ring tools.

Grind No.	Part No.	Measurements
1	Part 1	AE
2	Part 1	AE
3	Part 1	Roughness, SSD, Form, AE
4	Part 2	AE
5	Part 2	AE
6	Part 2	Roughness, SSD, Form, AE
7	Part 3	AE
8	Part 3	AE
9	Part 3	Roughness, SSD, Form, AE
10	Part 4	AE
11	Part 4	AE
12	Part 4	Roughness, SSD, Form, AE
13	Part 5	AE
14	Part 5	AE
15	Part 5	AE
16	Part 5	Roughness, SSD, Form, AE
17	Part 6	AE
18	Part 6	AE
19	Part 6	AE
20	Part 6	Roughness, SSD, Form, AE, Wear Measurement

As shown in Table 3, the grinding series for each ring tool consisted of 20 separate spherical surface generations utilizing six 40 mm diameter BK7 workpieces. The final ground surface of each workpiece was analyzed for roughness, SSD and form and AE measurements were made throughout the grinding series. Total volumetric tool wear measurements were also obtained at the end of the grinding series (Appendix B).

where, R is the desired workpiece radius-of-curvature, D is the ring tool diameter and ϕ is the approach angle of the grinding spindle relative to the workpiece spindle. The grinding zone is flood-cooled with temperature controlled (± 0.1°C) aqueous-based fluid[8] at 47 l/min (12.5 gpm).

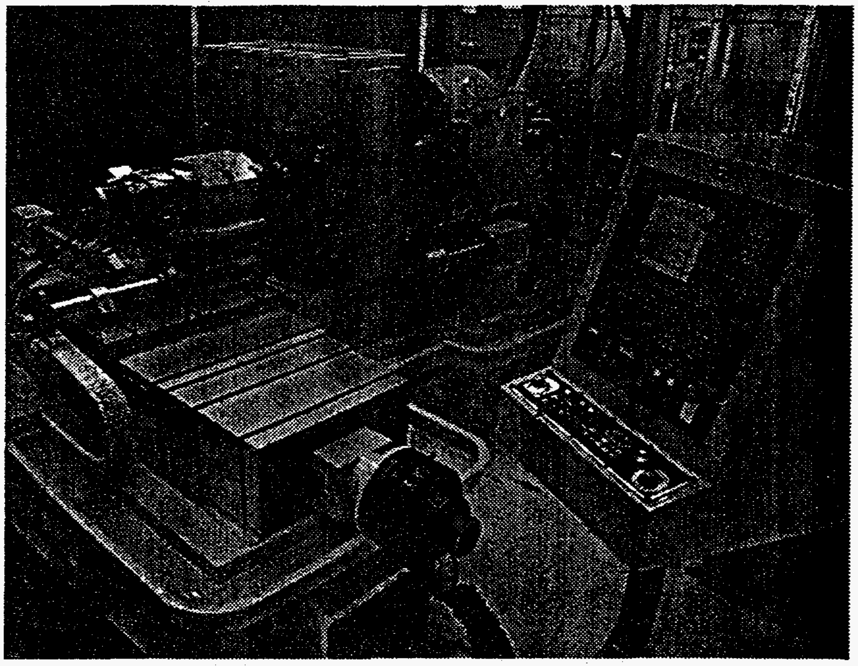


Figure 1 - The Moore T-base grinder provides a stiff experimental platform.

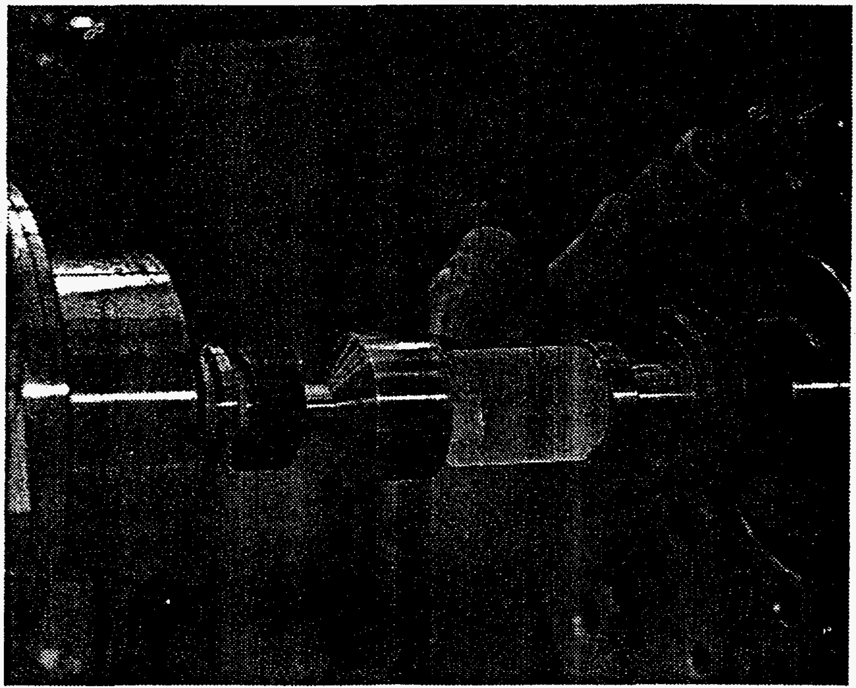


Figure 2 - Spherical surface generation on a BK7 glass workpiece.

Shown in Figure 3 is a photograph a diamond bronze ring tool mounted in a collet tool holder as used in our Westwind air-bearing spindle and also an unmounted tool. These particular ring tools have a bond OD and ID of 52 mm and 48 mm respectively, a cup height of 30 mm and 44 mm long 15.8 mm diameter shank. We typically use a 3-step grinding process which uses three diamond grit sizes: a coarse tool (approximately 75 µm grit), a medium tool (10-20 µm) and a fine grinding tool (2-4 µm).

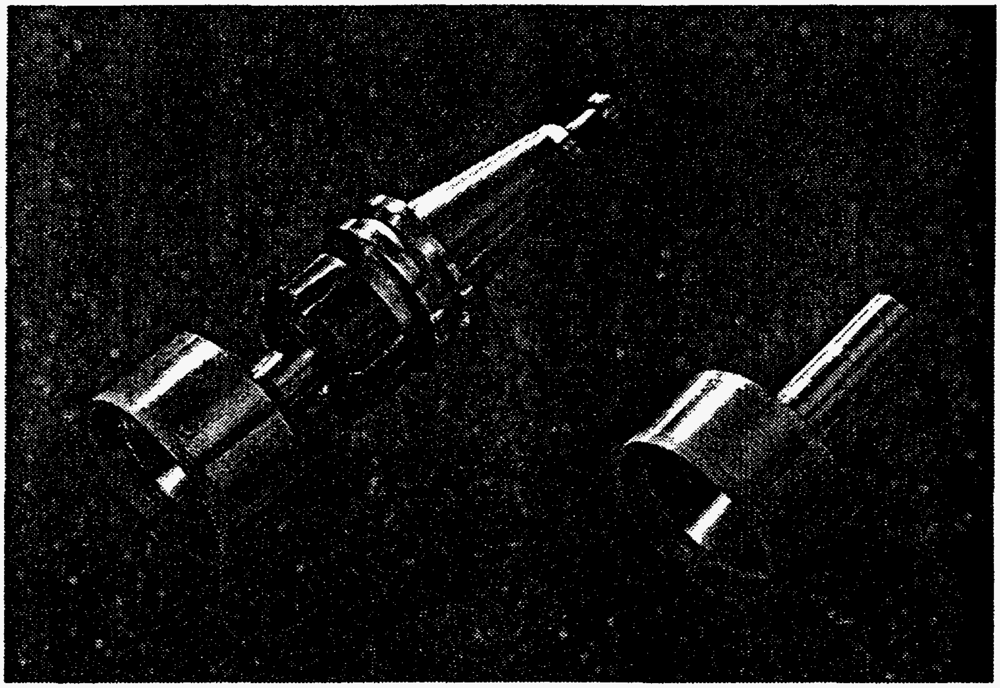


Figure 3 - Shown above are a ring tool mounted in a collet type tool holder and an unmounted ring tool.

Performance Evaluation Methodology

The ultimate goal of this work is the ability to specify ring tool properties based desired performance. An essential first step in achieving this is to first be able to correlate performance among various ring tools. Figure 4 is a flow diagram of our standardized procedure for characterizing and evaluating fixed abrasive ring tools. The specific evaluation techniques employed for each step will vary depending on the manufacturing goals and the resources available.

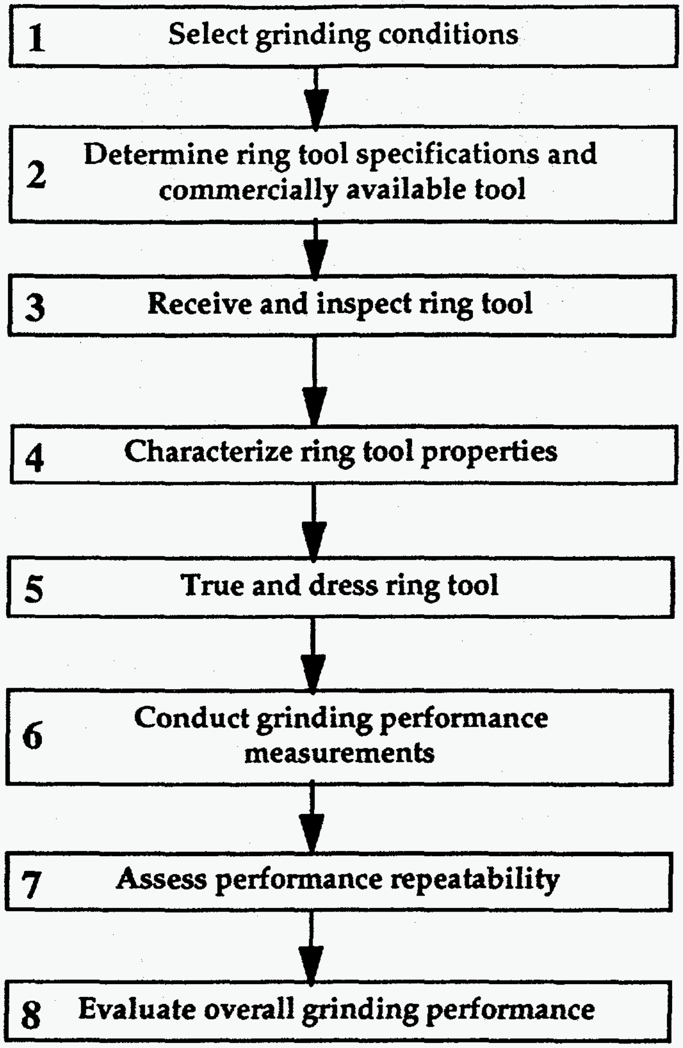


Figure 4. General ring tool characterization flow diagram.

Performance evaluation process:

1. Select grinding conditions
   Select grinding conditions consistent with workpiece material and goals.

2. Determine ring tool specifications and appropriate manufacturer
   The workpiece material and manufacturing goals dictate the approximate ring tool specifications and the selection of a vendor or multiple vendors is made according to manufacturing capabilities.

3. Receive and inspect ring tools

   This involves verifying dimensional accuracy and visual inspection of the ring tool bond integrity (cracks, large pull outs, etc.).

4. Characterize and record ring tool properties

   This step includes both the measurement of ring tool properties and the recording of certain properties as specified by the manufacturer (Figure 5a).

5. True and dress the ring tool

   A standardized method of truing and dressing is important to ensure that the ring tools begin their evaluations under similar conditions. The method which we choose to use involves the use of 120 grit SiC grinding wheels to true the face, ID and OD of the ring tool bond while it is mounted in the grinding spindle. Truing is then followed by stick dressing on all three surfaces with a 600 grit Al_2O_3 stick. We chose this method of truing because it allows the ring tool to be trued in the same grinding spindle in which it is used during the grinding process. We audit our truing effectiveness by measuring axial and radial motions using capacitance probes and a high speed data acquisition program. The measurement strategy uses the axis of rotation measurement standard (ANSI/ASME B89.3.4M) in determining axial and radial error motions. Dressing effectiveness is audited intermittently through the use of SEM analysis and more frequently through process measurements such as AE, grinding forces and part quality.

6. Conduct grinding performance measurements

   The grinding performance evaluation includes a variety of tests to characterize various performance measures (Figure 5b).

7. Assess performance repeatability

   As shown in Figure 5c, performance repeatability includes a number of subtopics. Namely, it is important to examine repeatability of the same wheel throughout its lifetime, tool-to-tool repeatability and manufacturer-to-manufacturer repeatability. This characterization should entail a statistically significant number of surfaces to evaluate performance repeatability.

8. Evaluate overall grinding performance

   The ultimate evaluation of a ring tool is dictated by the individual goals of the end user. For example, the evaluation of a tool by a manufacturer requiring high part throughput may vary from the evaluation of the same wheel by a manufacturer requiring small batches of high quality parts.

Table 1 shows the measurements to be made during the evaluation and the corresponding measurements methods. We expect that the methods for performing these various measurements will evolve and expand as we receive feedback from industrial collaborators.

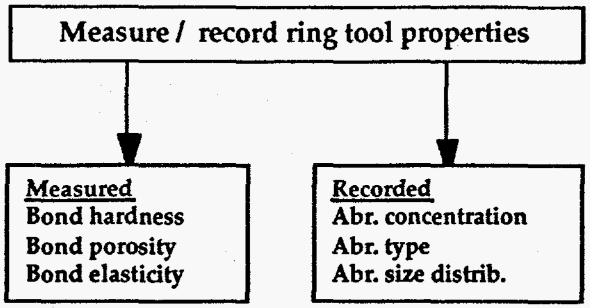


Figure 5a - A variety of ring tool properties will be measured / recorded to begin correlating performance with tool properties.

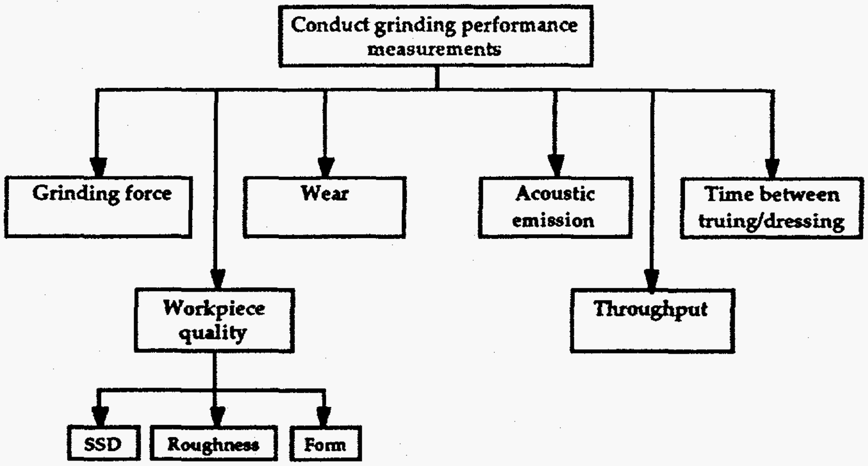


Figure 5b - Performance measurements can be broken down into several specific performance characterizations.

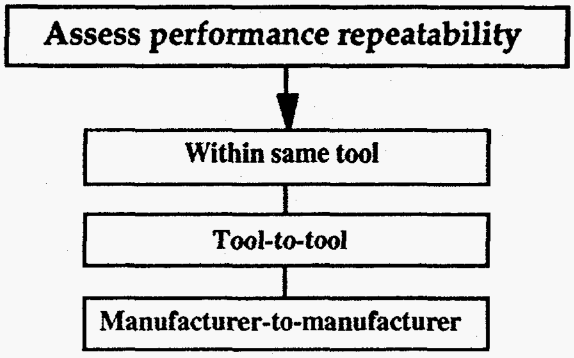


Figure 5c - Ring tool performance repeatability will be assessed at different levels.

Table 1 - Performance evaluation measurements and corresponding methods.

Ring Tool Properties	**Measurement Technique**
Bond hardness	Microhardness tester
Bond porosity	Ultrasonic tester
Diamond type	Manufacturer's specifications
Diamond size distribution	Manufacturer's specifications
Diamond concentration	Manufacturer's specifications
Diamond distribution in bond	SEM Analysis
In Process Evaluations	
Grinding forces	Force dynamometer
Acoustic emission	AE sensor
Performance Indicators	
Part quality	
- Surface roughness	Zygo Maxim and New View
- SSD	Dimpler
- Form	Zygo Mark IV Interferometer
- Waviness	Stylus profiler
Maximum in-feed rate	Performance vs. In-feed rate
Wear life	G-Ratio measurement
Time between dressings	Direct measurement
Material removal rate (normalized)	Direct calculation

Initial Experiments

This section describes in more detail a portion of the overall performance evaluation process in which three fine grinding ring tools with nominally the same specifications from different manufacturers (referred to here as A, B and C) were evaluated. It is of interest to determine our success in obtaining commercial ring tools from multiple vendors which duplicate the fine diamond ring tools currently used by the COM. All three tools were specified to be 2-4 μm diamond grit in a bronze bond. An attempt to make the bonds of similar hardnesses was made by specifying hardness values equivalent to a Norton N-hardness bronze bond. This evaluation subset included part quality measurements (surface roughness, subsurface damage, and form) and wheel wear measurements. Although the wheels were all made to the same specifications, it was of interest to investigate any performance differences, if any, among the three tools which could be attributed to different fabrication techniques.

In these tests, we examined the performance of the three ring tools and their abilities to produce smooth, low damage spherical surfaces on 40 mm diameter BK7 glass workpieces. The grinding procedure began with a coarse grit tool to grind the basic form, followed by a medium grit tool and ending with one of the three fine ring tools. The in-

Preliminary Results

We used a Zygo Maxim to measure the rms surface roughnesses of our test workpieces and the results are shown in Figure 6. Note that on some of the rougher parts, significant data drop outs were encountered. While the absolute accuracy of these measurements may be debated, we feel the Maxim will provide adequate relative roughness values to be used in our ring tool characterization process.

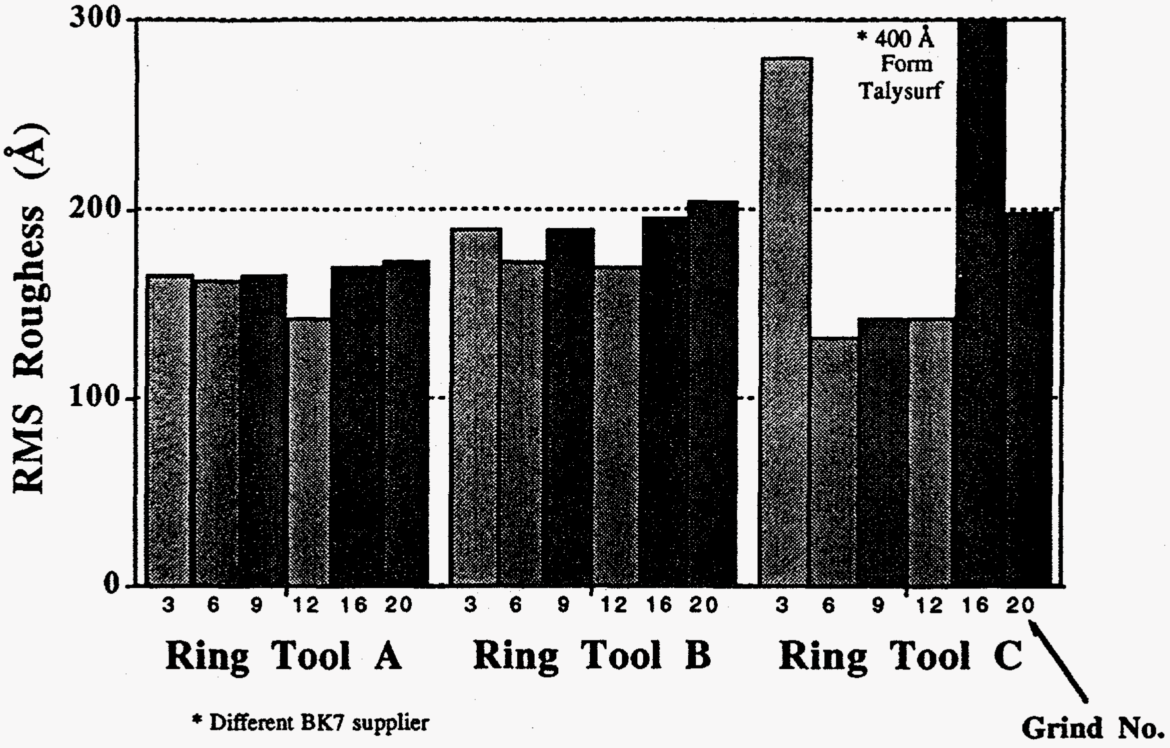


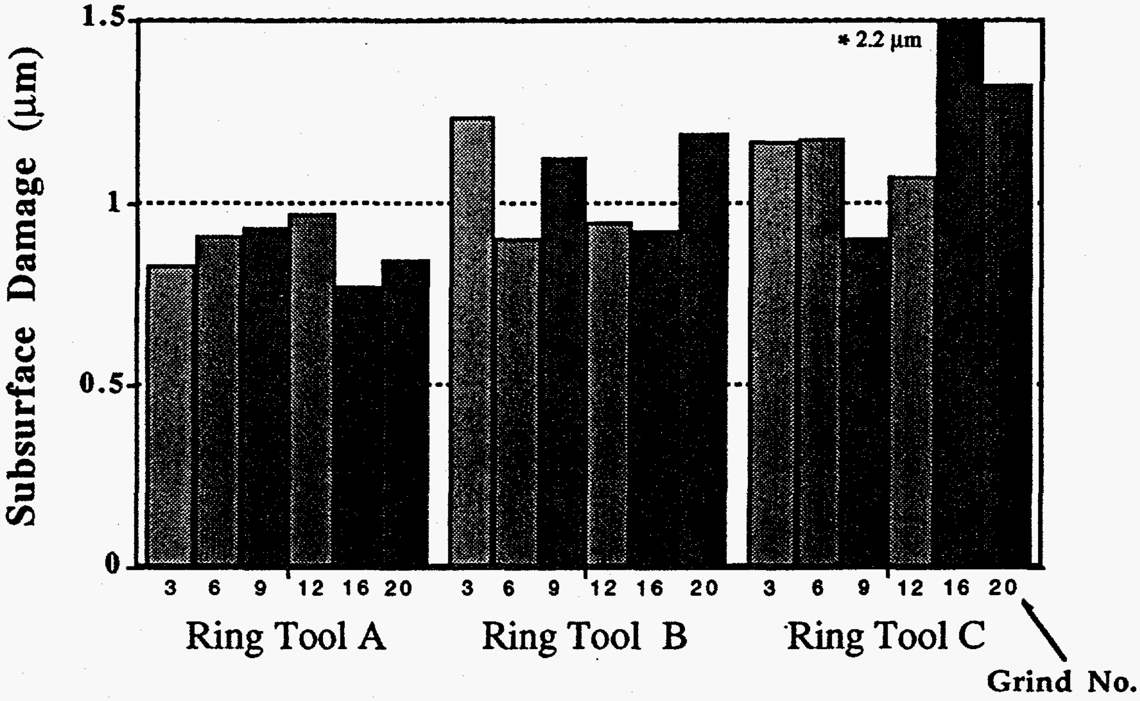
Figure 6 - Mean rms roughness measurements as measured by our Zygo Maxim (40x Mirau objective).

Shown in Figure 7 are subsurface damage measurements which were made using the dimpling technique on our test workpieces. The parts were etched for 30 seconds with 10% HF solution and the surface dimples were generated using a precision steel ball, a dimpling fixture and 1/4 µm diamond paste. It is of interest to note that in the Ring Tool C grinding series, a BK7 workpiece from a different supplier was inadvertently included. This particular workpiece had a significantly higher level of subsurface damage than any of the other workpieces. While this is only one data point, it does emphasize a possible sensitivity of workpiece quality with glass fabrication techniques.

Acoustic emission (AE) measurements were made during the grinding process with the three ring tools. A collet stop is used to provide position repeatability if a workpiece is removed from the spindle. When the workpiece holder is drawn into the collet during tightening of the collet nut, the base of the holder us securely pressed against the collet stop. The AE sensor was mounted to opposite end of the collet stop. AE signals generated by the grinding process for the three wheels were collected and downloaded into a personal computer for further processing. One assessment of the AE data was to calculate the rms values of the captured signals to provide a measure of AE magnitude. Results from various grinding passes during each series are shown in Figure 8.

Volumetric g-ratios were calculated for each of the three ring tools at the end of each 20 surface grinding series and are shown in Table 4. The data range values were obtained by calculating the difference between the maximum g-ratio and the minimum g-ratio for each wheel.

Radius-of-curvature measurements were made using a Taylor-Hobson Form Talysurf profiler for each of the six measured workpieces for each of the three ring tool grinding series. Table 5 displays average radius-of-curvature measurements (six measurements) and their corresponding ranges. It is important to note that truing the ID of the ring tool will directly affect the radius-of-curvature generated on the workpiece as the ID will increase as bond material is removed during truing.



• Different BK7 supplier

Figure 7 - Mean subsurface damage measurements obtained.

Table 4 - Measured volumetric g-ratio after 20 grinding operations.

	Average G-Ratio	Range
Ring Tool A	150	± 30
Ring Tool B	850	± 380
Ring Tool C	380	± 170

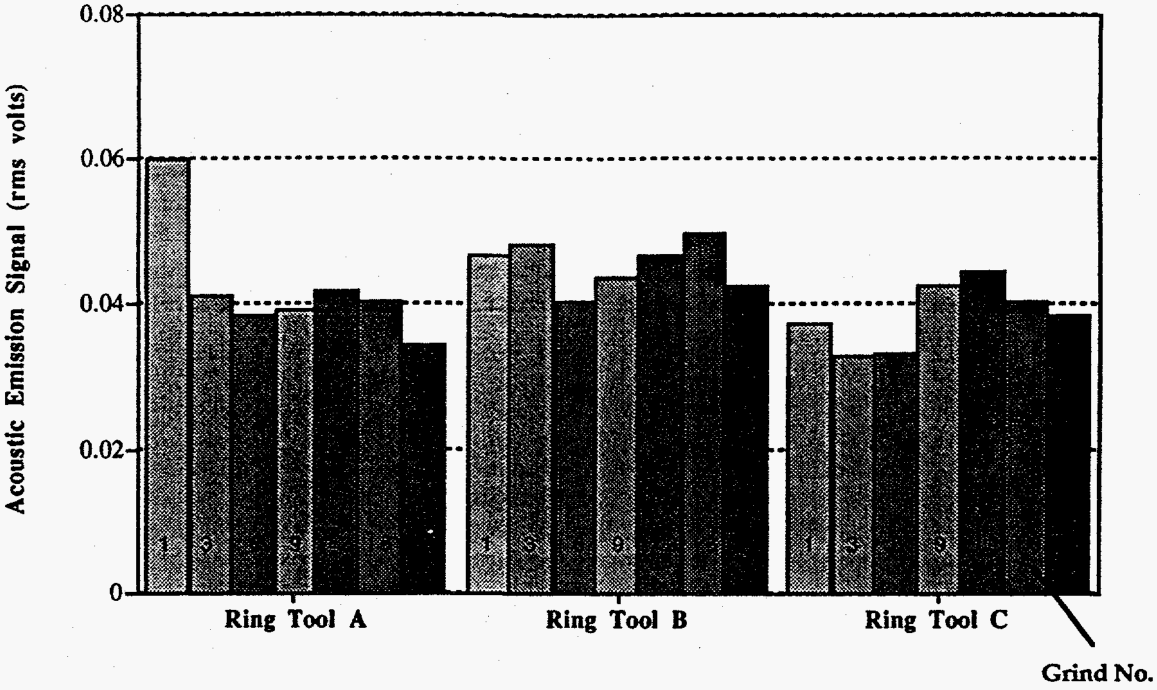


Figure 8 - Mean rms acoustic emission levels measured during grinding with the three test ring tools.

Table 5 - Average radius-of-curvature measurements

	Average Radius-of-Curvature (mm)	**Range (mm)**
Ring Tool A	171.8	±0.7
Ring Tool B	170.7	±1.0
Ring Tool C	171.0	±0.0

Discussion of Results

The preliminary results of our tests to evaluate three grinding wheels of nominally the same specifications as those used by the COM indicate that the measured performance differences among the three ring tools were small. The data in Figures 6, 7 and 8 demonstrated ranges up to 30% from the average reported values. Clearly, the errors introduced by the other grinding process input parameters (machine tool, process methodology, etc.) need to be evaluated to determine their influence in affecting the performance measurements.

As seen in Figure 6, ring tool C produced some of the smoothest parts, but at the same time showed the greatest variability among the three wheels. Results from an SEM analysis of the three wheels are shown in Appendix B. Recalling that the diamond sizes were specified to be 2-4 µm, it may be seen in Figure B1 that ring tools A and B appeared to have diamond well distributed throughout the bond. The larger dark areas appear to be porosity in the bonds. In contrast, ring tool C appears to have localized clustering of diamonds (shown in the upper-right and middle-left portions of the SEM). This non-uniformity of the diamond distribution in the bond may be responsible for the observed variability in the rms roughness measurements, but additional investigation is warranted.

Anomalous results were observed in the 5th (grind no. 16) workpiece of the ring tool C series. Upon investigating this, it was discovered that this particular workpiece came from a supplier different from the rest of the workpieces. Although both materials were specified as BK7, significant differences in workpiece quality measurements may indicate sensitivity to fabrication techniques of the material. This is only one data point and may or may not significant.

Conclusions and Future Work

We have established a standardized methodology for characterizing the performance of bound diamond grinding wheels used for fine grinding. Our initial goal is to minimize variations from confounding influences such as machine tool performance and dressing methodology, and to correlate wheel parameters with workpiece quality and throughput.

An application of this standardized procedure is to determine if wheels purchased from different manufacturers to nominally-identical specifications would perform similarly. A limited test of three different tools from different suppliers suggests one tool displayed both a greater level of part-to-part variability, while also producing the lowest values of roughness. SEM micrographs of this tool indicate a potential correlation between this tool's performance variations and localized-clustering of the diamond. Of the other two tools, one produced somewhat smoother surfaces with a greater level of repeatability. We did not assess tool-to-tool variability from each supplier in this study.

An important near-term goal for this project is to obtain larger statistical samples for a clearer assessment of repeatability. In addition, we will consider using materials such as sapphire and fused silica in order to accelerate the wear behavior of the tools. This will allow us to use wear life between dressings or truing as a tool performance indicator.

Our overall goal in working with COM and APOMA is to optimize tooling for a material removal process that yields high quality surfaces. Therefore, we are collaborating with wheel manufacturers and the Industrial Diamond Association to identify both commercially-available tools and new tooling concepts to achieve this goal. A wheel characterization procedure, such as the one described here, is instrumental in evaluating progress in this development program.

Acknowledgments

This work was performed in collaboration with the Center for Optics Manufacturing (COM) in Rochester, NY and the American Precision Optics Manufacturing Association (APOMA). We would also like to recognize Blaine Beith and Tony Demiris of LLNL for their participation and efforts in this study.

Appendix A

Volumetric Ring Tool Wear

The volumetric tool wear was calculated by using the measured width of the wear land on the ring and the in-feed angle of the ring tool (Figure A1).

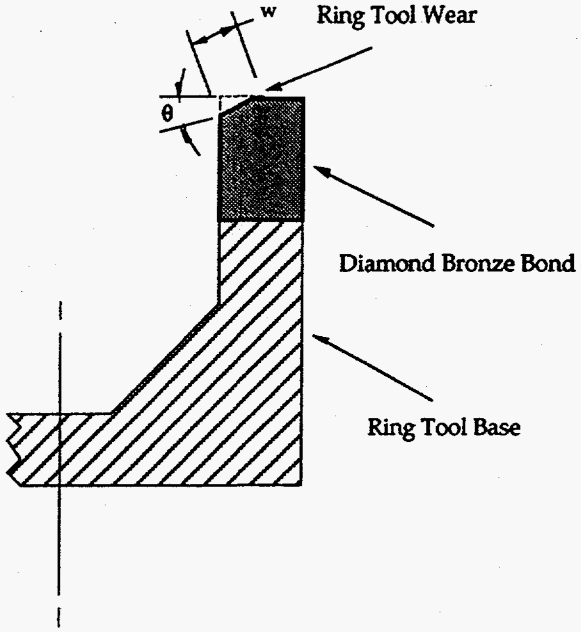


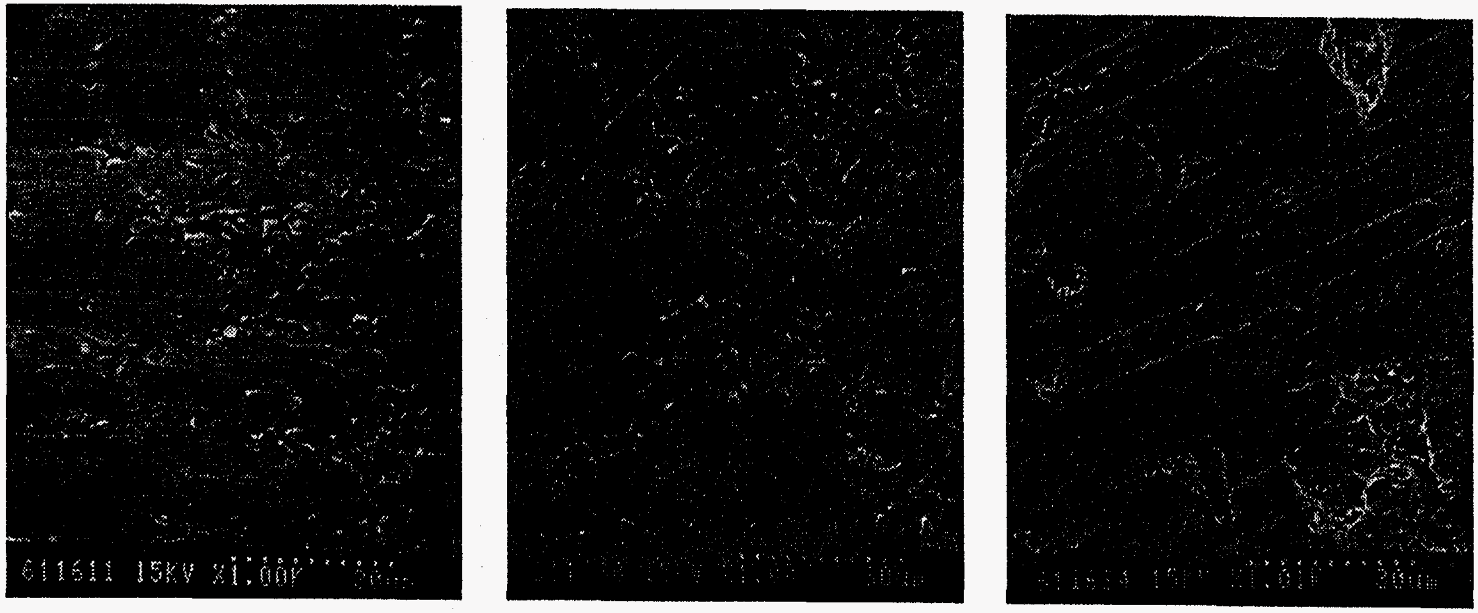
Figure A1 - Ring tool volumetric wear schematic.

The wear volume of the ring tool is then calculated as

$$V = \pi R W^2 \cos\theta \sin\theta \qquad \text{Eq. (2)}$$

As we have noted in previous experiments and as reported by the COM[9] , the rate at which the ring tool bond wears varies with the total amount of grinding performed by the tool. That is, the calculated grinding ratio when the ring tool is freshly trued and dressed will likely be different from the grinding ratio when the tool is worn. It is important that the tools under consideration all begin under the same conditions (trued and dressed) before beginning this evaluation.

Appendix B



Ring Tool A

Ring Tool B

Ring Tool C

Figure B1 - In these SEM micrographs, Ring Tools A and B appear to have well distributed diamond grit throughout the bond. Ring Tool B, in contrast, appears to have localized clusters of diamonds present in the bond.

---

[1] C. P. Bhataja, *Performance Evaluation of Grinding Wheels*, Society of Manufacturing Engineers, Dearborn, MI, MR87-815 (1987).

[2] K. V. Kumar and M. C. Shaw, "A New Method of Charakterizing Grinding Wheels," *Annals of CIRP* 28(1), 205-208 (1979).

[3] J. Verkerk, "Final report concerning CIRP Cooperative work on the characterization of grinding wheel topography," *Annals of CIRP* 26(2), 385-395 (1977).

[4] G. Spur and C. Stark, *Methods for Testing Grinding Wheel Quality*, Society of Manufacturing Engineers, North American Manufacturing Research Institute, Dearborn, MI, (1984), pp. 339-346.

[5] H. H. Karow, Fabrication Methods for Precision Optics, Wiley and Sons, Inc. (1993).

[6] G. E. Storz, II and T. A. Dow, "Cup Wheel Grinding Geometry," *Proceedings of ASPE 1993 Annual Meeting, Raleigh, NC*, 105-108 (1994).

[7] W. Zschommler, Precision Optical Glassworking, SPIE Volume 472 (1984).

[8] We are currently using Challenge 300HT grinding fluid from Intersurface Dynamics Inc., Bethel, CT.

[9] Presented at the OPTIFAB meeting at COM, October, 1994.