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to Optimize Tooling for Grinding Brittle Materials**

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

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Working with the Superabrasives Industry to Optimize Tooling for Grinding Brittle Materials*

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

Fred A. Gray
Industrial Diamond Association

Introduction

The optics manufacturing industry is undertaking a significant modernization, as computer-numeric-controlled (CNC) equipment is joining or replacing open-loop equipment and hand lapping/polishing on the shop floor.¹ Several prototype CNC lens grinding platforms employing ring tools are undergoing development and demonstration at the Center for Optics Manufacturing in Rochester, NY, and several machine tool companies have CNC product lines aimed at the optics industry.² Benefits to using CNC ring tool grinding equipment include: essentially unlimited flexibility in selecting radii of curvature without special radiused tooling,³ the potential for CIM linkages to CAD workstations, and the cultural shift from craftsmen with undocumented procedures to CNC machine operators employing computerized routines for process control. In recent years, these developments have inspired a number of US optics companies to invest in CNC equipment and participate in process development activities involving bound diamond tooling.⁴ This modernization process extends beyond large optics companies that have historically embraced advanced equipment, to also include smaller optical shops where a shift to CNC equipment requires a significant company commitment.

An essential element that must accompany the development of any new CNC grinding equipment is a corresponding material removal process that meets customer requirements for workpiece quality, throughput, and labor cost. The elements that contribute to the grinding material removal process are diagrammed in Figure 1, and include the machine tool, grinding wheel, workpiece, environmental variables such as temperature and vibration, and specific process choices, such as the speeds, feeds, and dressing/truing methodologies. Among these elements, the grinding wheel appears to be the least characterized element and has undergone the least optimization, particularly for the grinding of brittle materials such as glass.

This paper addresses our efforts to optimize fine grinding wheels to support the new generation of CNC equipment. We begin with a discussion of how fine grinding fits into the optical production process, and then describe an initiative for improving the linkage between the optics industry and the grinding wheel industry. For the purposes of this paper, we define fine wheels to have diamond sizes below 20 μm , which includes wheels used for what is sometimes called medium grinding (e.g. 10-20 μm diamond) and for fine grinding (e.g. 2-4 μm diamond).

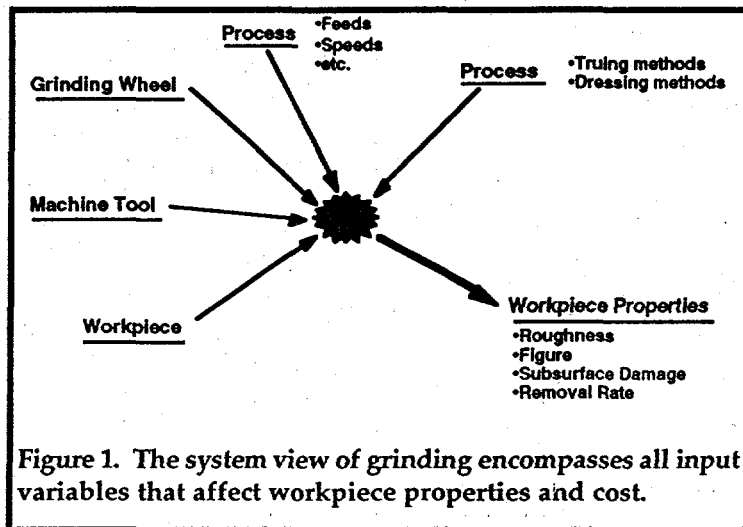


Figure 1. The system view of grinding encompasses all input variables that affect workpiece properties and cost.

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Ring Tool Grinding in Optics Manufacturing

The key metrics for assessing the benefits of a finishing processes include the quality, cost, and throughput of the *completed* workpiece. Thus the benefit of incorporating a new CNC grinding process will be judged not only by the speed and quality of grinding, but also on how grinding affects the entire finishing process, particularly the cost of the subsequent polishing operation. It is important to note that production costs depend not only on machine time, but also embody all labor requirements, such as handling, washing, blocking/deblocking, machine set-up, truing, and dressing.

Two typical production scenarios,⁵ where CNC ring tool grinding is employed for precision optics, are shown in Figure 2. The upper diagram shows a "2-wheel" process where the final grinding operation employs a 10-20 micron diamond wheel, which produces a high quality matte finish of about 2000 Å rms. The workpieces are then polished, using either high-speed polyurethane pads or standard pitch polishing. The lower production chart shows a "3-wheel" process where a fine grinding operation uses a 2-4 micron diamond wheel.

Here the fine ground surface might have a finish of 80-150 Å rms and be characterized by a morphology of small fractures on a relatively smooth (ductile ground) background.

For both scenarios, the key is to minimize the total labor time to repeatably produce a part. Most companies employ the 2-wheel process where the requirement of the medium grinding step is to repeatably produce high quality matte finishes at very high in-feed rates. Alternatively, the 3-wheel process employs a finer diamond wheel to significantly lower the roughness and subsurface damage, while benefiting from a higher removal rate and better figure control than in polishing. In the 2-wheel process, a longer polishing cycle substitutes for the fine wheel used in the 3-wheel process.

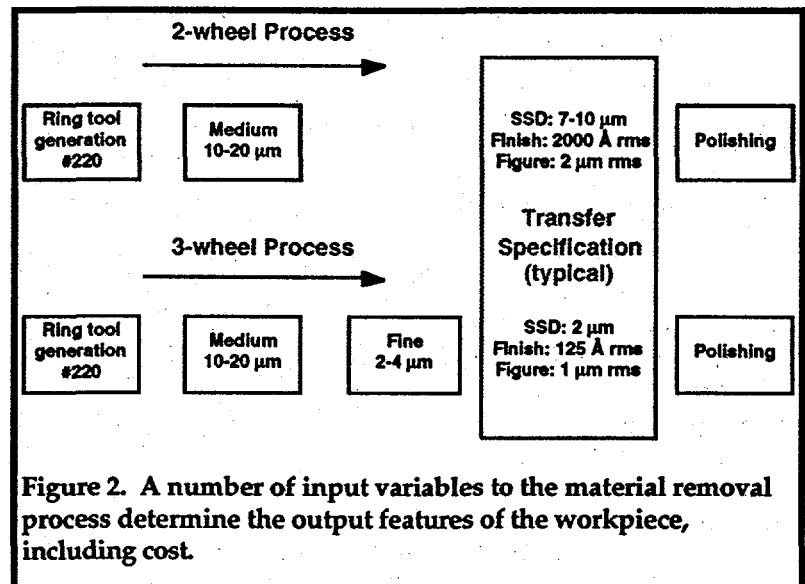


Figure 2. A number of input variables to the material removal process determine the output features of the workpiece, including cost.

The complete analysis of the relative merits of the two processes involves the details of the machining platform(s), the level of skill of the polishing technicians, grinding process choices, etc. and is well-beyond the scope of this talk. However, a key issue in assessing the relative benefits of a 3-wheel vs. a 2-wheel process lies in the trade-off between subsurface damage and figure error as the part moves from grinding to polishing. The subsurface damage from the medium grinding operation might be several times higher than the figure error. Thus when the part is being polished, the optician must maintain or improve the figure tolerance while the subsurface damage is being removed. For the fine ground part, the figure errors and the subsurface damage are on the same order of magnitude, offering the optician the potential for converging to the figure and finish specifications with similar required amounts of material removal.

From this analysis, two goals of grinding process development can be formulated, where wheel optimization is an essential element. For the 2-wheel process, it would be beneficial to improve the subsurface damage to a depth of a few micrometers, to more closely approximate the figure error. For the 3-wheel process, an ultimate goal is to completely eliminate the need for post-polishing. However, a more likely near-term goal is to sufficiently converge on the combined specifications of figure, finish, and subsurface damage so that only a very brief polishing operation is required, primarily to reduce scatter and improve cosmetics. Because polishing is typically the rate limiting step, improving the

grinding operation in order to shorten the polishing operation to the same order of time as the grinding steps, will improve the production flow so that all of the adjoining operations have approximately the same rate of throughput.

The Wheel Industry

Table 1 shows the relatively small number of companies that we have identified as manufacturers of fine diamond wheels. We estimate that fine diamond wheels are 1-5 percent of the diamond wheel industry. Most of the industrial diamonds going into fixed abrasives are used for concrete cutting/grooving, quarrying, deep drilling, and carbide grinding.⁶ Because fine wheels are such a small market segment, there is little motivation for wheel makers to devote significant resources for optimizing or developing wheels for optics applications. Exceptions to this rule include a few companies that are closely coupled with optics manufacturers and companies that support the ceramics industry, where there is a substantial technical overlap with glass grinding.

Survey that Identifies Grinding Problems with Wheels

Our group at LLNL was invited to report on a casual survey of optics companies at the 1995 Annual Meeting of the Industrial Diamond Association (IDA).⁷ The survey asked optics companies about their satisfaction with their wheels and their wheel suppliers. Most survey responses were anecdotal (and unscientifically analyzed), but there was a clear thread of concern about the repeatability of wheels from their current sources, as well as a frustration of not being able to buy wheels from additional sources, without a lengthy trial and error period.⁸ At this meeting, there was also an optics company representative who very strongly suggested that the communication between wheel makers and users was sufficiently poor that it precluded the effective specification of wheel

Table 1. Manufacturers of bound diamond tooling with diamond sizes $\leq 20 \mu\text{m}$.

Company Name	Contact	State	Phone	Fax
Abrasive Technology, Inc.	Loyal M. Peterman, Jr.	OH	614-548-4100	614-548-7617
Action Superabrasive Products, Inc.	Joe Haag	OH	216-688-8505	216-688-8518
Alpex Wheel Company	Steve Michel	NJ	201-871-1700	201-871-1521
Applied Superabrasives, Inc.	James Godin	CT	203-654-1780	203-654-1782
Braemar	Chuck Phillipone	AZ	602-966-9311	602-966-2273
Diagrand, Inc.	Donald P. Sommer	IL	708-460-4333	708-460-8842
Diamond Devices, Inc.	Mike Wire	CA	916-823-3333	916-823-7618
Diamond Fabricators, Inc.	Mark Greathouse	OH	216-942-7400	216-942-3183
Fuji Die	Mr. Vasuchika Fukaya	Japan	81-3-3579-7181	81-3-3756-7381
Fujimi	Charles Tiedman	CA	510-460-0601	510-460-0419
General Industrial Diamond Co., Inc.	Ronald M. Schwarz	NJ	201-884-2500	201-884-0392
Greenlee Diamond Tool Co.	Glen P. Rosier	IL	708-803-7366	708-803-9761
Inland Diamond Products	Dennis R. Raffaelli	MI	313-858-2330	313-589-0499
LOH	Mike Krueger	WI	414-255-6001	414-255-6002
Lunzer Industrial Diamonds, Inc.	J. Peter Lunzer	NJ	201-794-2800	201-794-2338
National Diamond Laboratory	Peter Skorewicz	NY	914-737-3774	914-737-1774
Noritaki	Joseph Michaelic	OH	800-688-8234	513-771-4006
Norton Co. Diamond Tool Div.	Dick Sioui	MA	508-795-2364	508-795-5507
Scomac	Larry Scott	NY	716-494-2200	716-494-2300
Superabrasives, Inc.	Charles A. Halprin	MI	313-348-7670	313-348-8037
The Wickman Corporation	Ben Stormes, II	MI	1-800-367-9398	810-548-3831
Universal Superabrasive		IL	708-238-3300	708-238-3315
Web Industries	Bud Begone	NJ	201-335-1200	201-335-7054
Wendt Dunnington Co.	Daniel Herzog	PA	610-458-5181	610-458-8903
Wickman's Diamond & CBN Products	Fred Lindblad	MI	313-548-3822	313-548-3822
Ernst Winter & Son, Inc.	Jerry L. Martin	SC	803-834-4145	803-834-3730

performance requirements.⁹ The IDA members were quite receptive to the survey input and were open to ways to improve the dialogue with wheel users.

LLNL and the IDA are currently updating this survey, with input from both wheel users and wheel makers. From the wheel makers' point-of-view, we hope to learn how important fine wheels are to their overall business, their satisfaction in meeting the needs of the fine wheel users, and what considerations might lead to better tool optimization. From the users' point-of-view, we hope to learn how satisfied they are with their wheels and wheel suppliers, and do they think that improved tooling would improve their productivity (in the presence of other limitations in their process). All wheel makers and wheel users who would like to participate in this survey should contact one of the authors for a copy of the survey. This is an ideal opportunity for the fine grinding community to formulate a message for the wheel manufacturers in terms how they might better service their customers. The Industrial Diamond Association has invited the results of this survey to be published in their quarterly magazine *Finer Points*. Some survey results will be presented as part of this paper, but the complete results as well as any actions initiated by the results will be presented at *SuperTech 1996* (Superabrasives Technology), a workshop that will be held at LLNL on November 7-8, 1996.¹⁰

Assessing Wheel Performance from the Users' Point-of-View

In responding to industry concerns that fine diamond wheels (particularly 2-4 μm wheels) are not sufficiently optimized, we are assessing the performance of wheels in terms of repeatability and overall quality. Our first effort was to formalize the standard cutting test that most users employ: examine the roughness, subsurface damage, and figure errors produced during a grinding test.¹¹ The formalization comprises running the same tests for all evaluations to allow apples-to-apples comparisons of wheel performance, and the control of various independent variables, such as *standardized truing/dressing procedures* and the use of *identical sequences for breaking in a tool*. Typical data from this type of evaluation are presented in Figure 3, where the relative performances of metal-bonded wheels are compared to Cu-resin-bonded wheels.

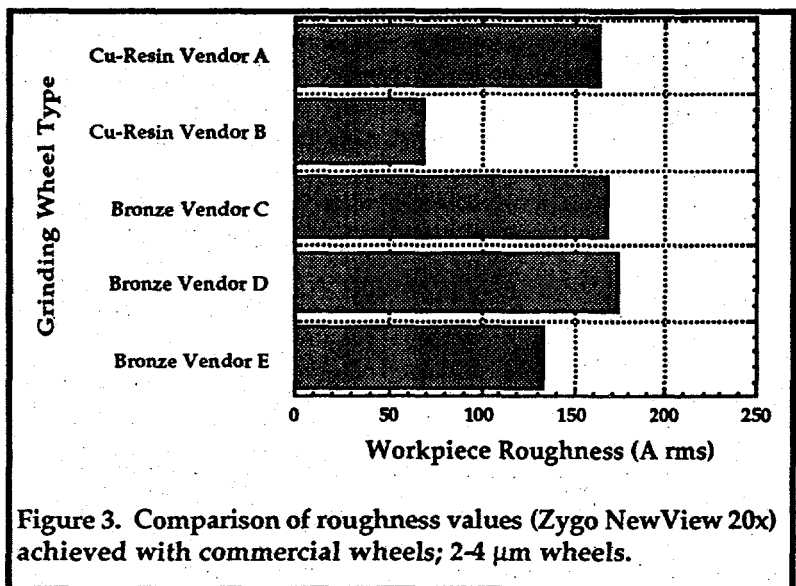


Figure 3. Comparison of roughness values (Zygo NewView 20x) achieved with commercial wheels; 2-4 μm wheels.

The metric that an optics company ultimately uses in judging tool performance is how well it meets requirements for part quality and cost per workpiece (labor plus materials). Thus, a user's evaluation of *grindability* for a particular tool, includes a weighted judgment of how well the tool met all of the desired performance specifications. This type of assessment might be viewed as either a qualitative or quantitative evaluation such as that diagrammed in Figure 4a. The weighting coefficients would reflect the user's specific application, and his method to optimize the production process. Although it is doubtful that users would carry out this evaluation in a rigorous sense, clearly some assessment like this must take place when a specific tool is selected among a field of several candidates. In this diagram, the composite grindability *G* represents a figure-of-merit for the selection of grinding wheels.

Assessing Wheel Performance from the Wheel Makers' Point-of-View

The metric used by the wheel maker in selecting a wheel design for meeting a customer's requirement will be cast in terms of the variables involved in making the wheel, such as those enumerated in Figure 4b. In general, the selection of wheel ingredients and wheel style for meeting a performance requirement are proprietary information. It is interesting to note that the *cost* figures-of-merit for the user and the wheel maker may have very different connotations.

$$\begin{aligned}
 (a) \quad G_{user}^2 &= a_1 (rms)^2 + a_2 (SSD)^2 + a_3 (figure)^2 \\
 &+ a_4 (g - ratio)^2 + a_5 (feedrate)^2 \\
 &+ a_6 (effort)^2 + a_7 (cost)^2 \\
 (b) \quad G_{maker}^2 &= b_1 (diamond)^2 + b_2 (bond)^2 + b_3 (filler)^2 \\
 &+ b_4 (porosity)^2 + b_5 (concentration)^2 \\
 &+ b_6 (procedure)^2 + b_7 (cost)^2
 \end{aligned}$$

Figure 4. Figures of merit (FOM) for grinding wheels. (a) qualitative FOM used in selecting a wheel for grinding lenses – users' point-of-view; (b) qualitative FOM used in selecting wheel ingredients to meet an application – wheel makers' point-of-view.

Lack of Common Language

In considering the two thought schemes for evaluating a wheel as depicted in Figure 4, there is clearly a lack of common language between the user and wheel maker. The user defines grindability in terms of the performance of the wheel for a specific application, while the wheel maker considers wheel performance from a consideration of what types of ingredients are used. This view is clearly exaggerated and of course both groups generally make an attempt to incorporate the others' point-of-view. However, there typically is not an open dialogue between the two groups that would enable the correlation between wheel ingredients and the user's performance indicators. This lack of correlation between G_{maker}^2 and G_{user}^2 is especially a problem for fine wheels because there is minimal market incentive for most wheel companies to invest in a program of optimization.

A Proposed Solution to a Better Dialogue

A potential bridge between the somewhat disparate languages of the wheel user and the wheel maker may lie in the form of a set of intermediate performance indicators for the wheel, which are sensitive to wheel ingredients, but can also be correlated with wheel performance in the user's application. We are proposing a set of well-defined wheel evaluation tests, each of which is sensitive to a key performance property of the wheel. This is a very different approach from the performance evaluation test mentioned earlier, where specific workpieces are ground and then examined for figure, finish, etc. These proposed tests might include wheel hardness, thermal conductivity, friability, etc. A preliminary collection of performance figures-of-merit are given in Figure 5, where they are all summed (sum of squares) to form a composite FOM to enable a selection of one wheel over another. The weighting coefficients are determined by identifying relative importance of the performance specifiers for a given application. Both the user and wheel maker internally translate the format of Figure 4 into the familiar descriptors of Figure 2, and which largely involve proprietary information.

Composite Figure - of - Merit $G^2 = \sum_i a_i (FOM_i)^2$ FOM_i = elemental performance metrics a_i = application specific weighting coefficients	$ \begin{aligned} G^2 &= a_1 (hardness)^2 \\ &+ a_2 (friability)^2 \\ &+ a_3 (clearance)^2 \\ &+ a_4 (protrusion)^2 \\ &+ a_5 (temp stability)^2 \\ &+ a_6 (dressability)^2 \\ &+ a_7 (self sharpening)^2 \\ &+ a_8 (heat transfer)^2 \\ &+ a_9 (grit shape)^2 \\ &+ a_{10} (chem stability)^2 \end{aligned} $
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Figure 5. Proposed performance figures-of-merit can bridge between user requirements and proprietary wheel information.

A Voluntary Product Standard

During the next several months LLNL and the IDA will be investigating whether such a list of performance specifiers constitutes a useful approach for reconciling user requirements and wheel preparation methods. In the event that there is a clear message from the optics industry that this type of system is beneficial, and that wheel makers can relate these performance specifiers to composition, then it may be appropriate to adopt these performance specifiers as a voluntary product standard. Clearly, not all wheel companies and optics companies would need to participate, but if several agreed to a trial of the system, then the value of such a system could be assessed.

Hardness as a Performance Indicator

Hardness or resistance to indentation is one example of a performance indicator that relates to both the wheel ingredients and performance as observed by a user. Hardness has been used by many wheel manufacturers as a performance indicator. It typically refers to resistance to abrasion, but clearly is related to the mechanical properties of the bond and the bond-grit system. There is only a loose connection among the common letter hardness grades among wheel companies, although an "N-bond" is usually considered to be "medium".

We are promising a testing procedure for one aspect of hardness: resistance to indentation. This concept has a rich history in the mechanics literature,¹² but standardized testing procedures focus on plastic deformation, and usually require a polished surface for sizing of indentation marks. Because the wheel is a composite material with a high diamond concentration, polishing the wheel surface for inspection of micro-hardness indentation marks is problematic. Thus there is a need for an alternate instrumentation approach for measuring hardness.

Another experimental methodology for characterizing hardness is measuring the increase in force as an indenter is pressed into the surface.¹³ The indentation force is plotted versus indentation depth for both the loading and unloading operations. By analyzing the curves, it is possible to assess both elastic and permanent deformation. The area under the curve can be integrated to assess deformation energy.

The indentation properties of the wheel that relate to its performance may encompass plastic, elastic, and fracture mode behavior. These, in turn, may relate to the performance of fine grinding wheels by reflecting the ability of the wheel to accommodate various disturbances or errors that may lead to large grit-to-glass forces and commensurately high subsurface damage. It may not be important which of the three above deformation modes occur, as long as the wheel provides sufficient accommodation for limiting single-grit force excursions.

Figure 6 shows plots of force versus indentation, where a 1 mm radius indenter was indented to a maximum of 2 μm into a bronze bond wheel and a Cu-resin wheel. Clearly, the bronze bond tool exhibits higher force levels for the same indentation. Examining the unloading curves shows that there is permanent deformation, as illustrated by the force going to zero, prior to the indentation returning to zero. These measurements were taken using a stiff T-base machine tool as the feeding mechanism, an LVDT located very close to the indenter, and Kistler piezoelectric force dynamometer.

Finally, the resistance of the wheel to indentation might be expected to vary as a function of the size of the indenter. This would relate to the performance of the tool, as disturbances might span a wide range of spatial sizes. For example, the ability of the wheel to accommodate a solitary diamond that protrudes further from the bond than neighboring diamonds might ideally be tested using a very small-radius indenter. The ability of the wheel to accommodate waviness on the wheel due to truing errors, might ideally be tested by using a large-radius indenter.

Figure 7 shows how a hardness evaluation could comprise multiple tests that span a range of spatial scales. The three examples correspond to long, mid, and short spatial wavelengths (λ_{sp}). These correspond to wheel compliance as manifested by different spatial features on the wheel. A hardness test might target these different spatial scales using indenters with different radii-of-curvature (ROC). Finally, examples are given of the physical sources of disturbance corresponding to each spatial scale. A hardness characterization might encompass numerical values corresponding to each spatial scale.

Enabling Technologies

The optimization of grinding wheels, and their insertion into production practice may be coupled with the development of enabling technologies. For example, we have observed the performance of metal-bonded wheels to degrade more than resin-bonded wheels in the presence of machine vibrations. This observation may relate to the hardness concepts mentioned in terms of accommodating wheel motion errors. Thus, for some wheels to produce smooth surfaces, it may be necessary to employ stiff, well-damped machine tools. Therefore, the further development and availability of high quality machine tools may enable more success stories for fine grinding in US industry.

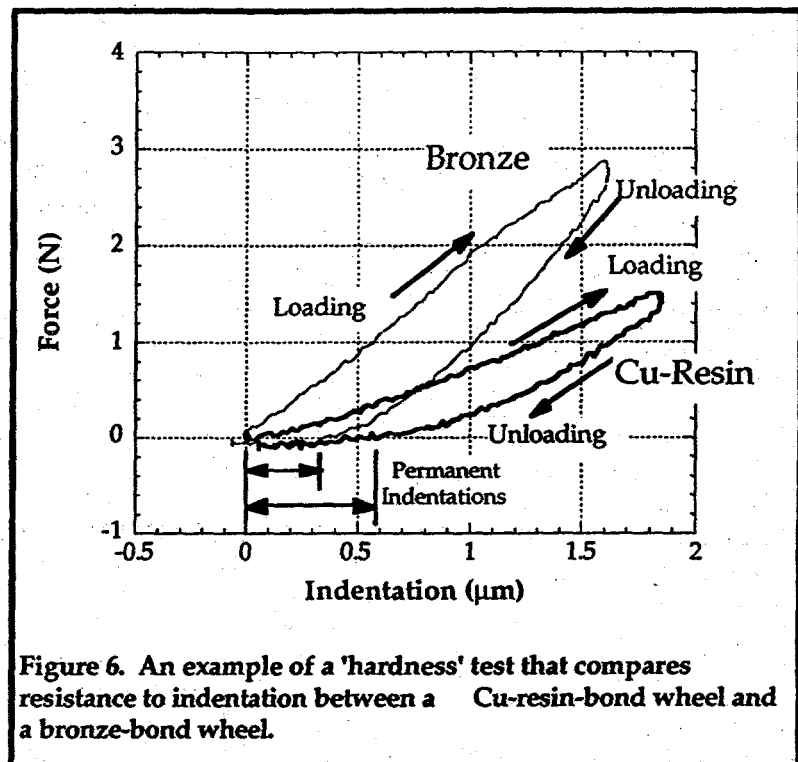


Figure 6. An example of a 'hardness' test that compares resistance to indentation between a Cu-resin-bond wheel and a bronze-bond wheel.

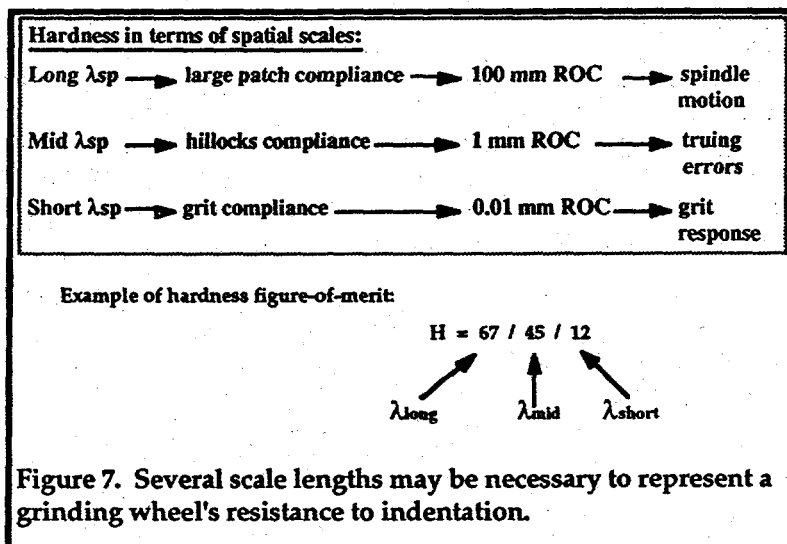


Figure 7. Several scale lengths may be necessary to represent a grinding wheel's resistance to indentation.

Although resin-bonded wheels may provide better levels of surface finish, their wear rates tend to be much higher than for metal-bonded wheels. During a production run, this increased wear quickly leads to an uncertainty in knowing the position of the tool relative to machine coordinates, and often the tool spends a significant duration performing 'air grinding.' A reliable, non-contact, tool-to-workpiece proximity sensor that functions under grinding conditions (i.e. fluid flowing and spindles running) would enable the position of the tool relative to the workpiece to be determined in real-time, for each workpiece. We have successfully demonstrated such a non-contact acoustic emission (AE) sensing scheme at LLNL,¹⁴ and will soon be installing a prototype in the production equipment at the Center for Optics Manufacturing. One of our goals is to use this AE sensing scheme to enable the production use of resin-bonded tools in the presence of extensive tool wear.¹⁵

Conclusions

The goal of this paper is to present an approach for improving the linkage between the users and makers of fine diamond grinding wheels. A promising avenue for accomplishing this is to formulate a voluntary product standard that comprises performance indicators that bridge the gap between specific user requirements and the details of wheel formulations. We propose a set of performance specifiers or figures-of-merit, that might be assessed by straightforward and traceable testing methods, but do not compromise proprietary information of the wheel user or wheel maker. One such performance indicator might be wheel hardness as measured by the resistance to indentation. Resistance to indentation may indicate the wheel's ability to accommodate geometric errors over several different scale lengths, while maintaining the grinding force below the level required for high quality grinding. In addition, we considered technologies that might be required to realize the benefits of optimized grinding wheels. A non-contact wheel-to-workpiece proximity sensor may provide a means of monitoring wheel wear and thus wheel position, for wheels that exhibit high wear rates in exchange for improved surface finish.

Acknowledgments

The authors would like to thank Blaine Beith for performing wheel evaluation tests mentioned in this paper, and Don Golini (COM) for interesting discussions regarding fine grinding.

Notes

¹ Pollicove, H. M., "The Center for Optics Manufacturing", 1994 Technical Digest for the Optical Fabrication and Testing Workshop, paper OWD1 (1994); Leshne, R. H., "Support for the US precision optics manufacturing base: The Center for Optics Manufacturing", *Proc. SPIE*, vol. 1168, 2-8 (1989).

² For example: CNC Systems, Ontario, NY; Loh Optical Machinery, Inc., Milwaukee, WI; Rank Pneumo, Keene, NH.

³ The extent to which these benefits can be realized depends upon the specific choices for which platforms are employed.

⁴ Ray Lacroix, President, American Precision Optics Manufacturers Association (APOMA), personal communication.

⁵ Some optical shops may employ a 1-wheel process for meeting some production requirements.

⁶ Gray, F., "A Look at the Superabrasives Industry Today," *Finer Points*, vol. 7, no. 4, 1995, pp. 8-10.

⁷ Taylor, J. S. and Piscotty, M. A., "Survey of Wheel Users and Review of Precision Machining at LLNL", Invited paper at IDA Annual Meeting, Tucson, AZ, April 1-5, 1995.

⁸ It should be noted that not all companies contacted had complaints about their wheel supplier, nor were all companies fully committed to transitioning away from loose abrasive lapping.

⁹ Vakiner, J., "What Tool Users Need to Know," Invited speaker at IDA Annual Meeting, Tucson, AZ, April 1-5, 1995.

¹⁰ *SuperTech 1996: Grinding and Machining Brittle Materials with Superabrasives* is being hosted by Lawrence Livermore National Laboratory and the Industrial Diamond Association, to be held at LLNL on November 7-8, 1996, just prior to the 1996 ASPE Annual Meeting in Monterey; for more information, please contact one of the authors.

¹¹ Piscotty, M. A., Taylor, J. S., Blaedel, K. L., "Performance Evaluation of Bound Diamond Ring Tools," *Optical Manufacturing and Testing*, Proceedings SPIE, vol. 2536, pp. 231-246 (1995).

¹² Johnson, K. L., *Contact Mechanics*, Cambridge University Press, New York (1987).

¹³ Polvani, R. S. and Evans, C., "Micro-indentation assessment of near surface material properties and subsurface damage in precision machining," in *Ultraprecision in Manufacturing Engineering*, Proc. of the International Congress for Ultraprecision Technology, May 1988, Aachen, pp. 271-286.

¹⁴ Taylor, J. S., Piscotty, M. A., Blaedel, K. L., Weaver, L. F., and Dornfeld, D. A., "Investigation of Acoustic Emission for Use as a Wheel-to-Workpiece Proximity Sensor in Fixed-Abrasive Grinding," *Proc. of the ASPE 1995 Annual Meeting*, American Society for Precision Engineering, 159-162 (1995).

¹⁵ Other issues, such as extreme non-trueness, may also limit the use of some wheels in the presence of extensive wear.