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Progress Toward a Performance-Based Specification for Diamond Grinding Wheels

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A key goal when buying a grinding wheel is to enable a grinding process to meet a workpiece specification or a production requirement such as throughput. However, the grinding material removal process is complex, and is influenced by a wide range of variables in addition to the grinding wheel, such as the machine tool, environment, coolant, process selections such as speeds and feeds, and the workpiece. Accordingly, it is often difficult to demonstrate a repeatable correlation between the grinding wheel and workpiece quality because of the difficulty in identifying, measuring and/or controlling all key parameters. The combination of an incomplete understanding of how wheel parameters affect workpiece quality, and the presence of unknown or uncontrolled system variables poses a severe problem when trying to improve a deficient grinding process. This situation is particularly aggravated for the fine grinding of brittle materials, when minimizing subsurface damage, roughness, form error, and waviness are all key objectives.

In a paper we recently presented to the American Society for Precision Engineering[1] [included here in the Appendix], we observed that grinding wheels are largely specified by ingredients, and are not formally associated with a performance requirement. For that process to be successful, either the wheel user or wheel maker must specify the connection between desired performance and choices for the ingredients. As illustrated in Fig. 1, there is system information that the wheel maker is probably not aware of, and proprietary wheel information where the user has no knowledge. This leads to the anomaly that either the wheel maker tries to design the wheel with incomplete knowledge and control of the user's grinding system, or the user is trying to select wheel ingredients with an incomplete knowledge of the proprietary issues associated with wheel fabrication. We propose that development of a set of well-defined and commonly available performance tests or metrics might allow the wheel to be objectively specified without direct reference to proprietary wheel ingredients or the ill-defined details of a specific application.

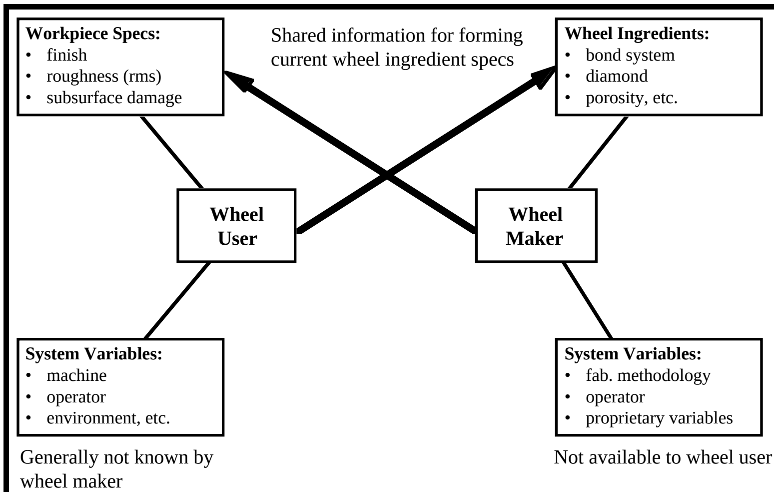

Figure 1. It is difficult to account for system variables in the current system of specifying wheel ingredients.

In this paper, we continue to investigate the process of specifying diamond grinding wheels, with a particular emphasis on the fine grinding of brittle materials. We begin with a discussion of the difficulties associated with specifying only wheel ingredients, and then consider alternatives, ranging from specifying wheel performance on well-defined machine tools for grindability testing, to specifying rigorously defined thermo-mechanical properties of the wheel. Each concept has advantages and disadvantages, but offers new possibilities for improving the communication between wheel users and wheel makers.

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Current methods for specifying grinding wheels

When grinding wheels are specified for something beyond a routine operation, there is often a dialogue between the user and the wheel maker about what wheels should be tried. Based on the experience of both, a wheel is then specified in terms of bond system, abrasive size, 'hardness', concentration, etc. If the user fully characterizes and explains his grinding system to the wheel maker, and the wheel maker knows the correlation between each wheel ingredient and desired grinding performance on the users type of system, then a wheel can be successfully specified. In the event that either party has less than complete information, it is likely that the choice of specified wheel will appear to be *incorrect*.

The hallmark of the current system for specifying wheels for challenging grinding problems is a trial-and-error process where a series of wheels are iteratively ordered and tried with different sets of wheel ingredients. The specifications for these wheels are based on wheel ingredients, not on a certification of performance, nor on any formal measurements of wheel properties.[2] This is not to imply that the wheel maker is not interested in wheel performance, nor in strict control of wheel quality. A number of wheel manufacturers do, in fact, have laboratories where wheel ingredients are carefully documented and controlled. Similar quality controls might also be placed on the methodologies for fabricating wheels (e.g. pressing and sintering).

However, the wheel ingredients (and fabrication methods) are the only aspects of the grinding process that are under the wheel maker's control. The complex system on the user's shop floor is precisely out of his control: machine tool variables, coolant application, environment, operator preferences, dressing and truing methods, etc. Thus, the only specification that the wheel maker can reasonably address regards the ingredients. The ANSI and ISO specifications for wheels are devoid of performance statements and only address geometric issues.[3]

As mentioned earlier and is illustrated in Fig. 4 in the Appendix, the user and the wheel maker approach the idea of optimizing the grinding process using different languages. As listed in Fig. 2a, the user employs a combination of surface finish, subsurface damage, cost, g-ratio, etc. to form a figure-of-merit for evaluating the success of the grinding operation. The wheel maker wants to address the needs of the user, but does so from the realm of what set(s) of ingredients, as listed in Fig. 2b, are optimal for a given work material and geometry, but probably will not be cognizant of the detailed considerations of rms finish and subsurface damage. Thus the wheel maker and the wheel user approach grinding optimization from different points-of-view.

Nevertheless, the wheel maker often shares in the responsibility for making the user's grinding system "work". The grinding wheel will not appear to be correct until the entire system performs properly. Stated differently, the wheel may be blamed if the system performs poorly, regardless of whether or not the problem lies with other system variables. This leads to the wheel vendor needing to understand much about the use of the wheel, e.g. dressing, truing, coolant compatibility, but usually with respect to a generic system. This may lead to a general knowledge about the performance attributes of key grinding wheels, but says little about what happens on a specific grinding system.

(a) User Metrics	(b) Wheel Ingredients
• Workpiece finish	• Diamond size - median
• Workpiece SSD	• Diamond size - distribution
• Workpiece figure	• Diamond type
• G-ratio	• Concentration
• Time between dressings	• Bond material
• Time between truings	• Porosity
• Dressability	• Filler materials
• Truability	• Proprietary ingredients
• Tendency to glaze	• Fabrication methodology
• Max mat'l removal rate	
• Power consumption	
• Coolant transport	
• Grinding temperature	
• Chemical stability	
• Cost	
• Availability	

Figure 2. The wheel user and the wheel maker view the grinding process with different variables.

Fine diamond wheels for brittle materials

The ability of the wheel vendor to make informed recommendations about which wheel design should be used is severely challenged when the application represents only a very small segment of his market, involves specialized grinding equipment, or involves workpiece specifications that are significantly more stringent than mainstream applications. This is the situation that exists for the fine grinding of glass and ceramics to optical tolerances.

Fine grinding is the operation that determines the final roughness, subsurface damage, and figure error for many ceramic components. It is also the operation that determines the economics of any subsequent polishing operations, such as for glass optics, where polishing tends to be the most expensive step in production. Fine grinding usually involves wheels with diamond sizes less than 20 µm (often 2-4 µm), and employs relatively expensive stiff computer-controlled grinding machines. Because the amount of material removed is relatively low and g-ratios are typically high, the usage (diamond consumed) of wheels for fine grinding is small when compared to diamond usage for quarrying, concrete cutting, and carbide grinding.[4]

Thus, a paradox exists: the most important grinding operation for manufacturing many economically important components, has minimal market pull for the grinding wheel industry to invest resources for developing and optimizing new wheels.[5,6,7]

Trial-and-error methodologies are inadequate for optimizing wheel specification

The current trial-and-error procedure for optimizing grinding wheels is inadequate. The employees and production machines who carry out the optimization are typically under intense pressure to generate products and not take the time to 'control all system variables so that good data is obtained.' The process of trying different wheels is centered around variations in what are often proprietary wheel formulations, thus the key experimental variables are out of the user's sphere of knowledge. If the grinding process is unsuccessful, it is difficult or impossible to look back at the wheel to certify if your knowledge of its ingredients is correct. A key inadequacy of the trial-and-error approach is that even if a successful wheel is identified, there probably has not been enough learned about the process to solve similar problems on different machines or with different work materials.

Inability to transfer wheel specifications among vendors

When a successful fine grinding wheel (for challenging brittle material applications) has been identified from a specific vendor, it is generally not possible to order a similarly performing wheel from another vendor. The elements of the purchase requisition are not tied to a performance requirement, but to an incomplete list of ingredients. Some wheel ingredients and fabrication steps are proprietary, thus are not known to the users and cannot be listed on the purchase requisition, nor transferred to other vendors. In addition, terminology for some wheel parameters is often qualitative or tied to a proprietary definition, such as *hardness* and *grade*. Although this is thoroughly reasonable from the wheel maker's perspective, it is a business risk to a wheel user to have only one source for a key grinding wheel. Yet the expense and distraction of going through a trial-and-error wheel identification program with multiple vendors is usually prohibitive.

In the remainder of this paper, we will explore a potential alternative format for specifying grinding wheels, that improves over the current trial-and-error optimization methods, and also provides a level of vendor transferability among wheel specifications while protecting proprietary wheel information.

Performance-based metrics offer a solution

Our earlier paper raised the idea that a set of objective, repeatable, reproducible tests of grinding wheel performance characteristics, or performance metrics, might serve as an intermediate language, that spans the gap between wheel ingredients and user requirements. This scenario is diagrammed in Fig. 3 and contrasts with the current situation depicted in Fig. 1. The focus of both the wheel user and the wheel maker are on the performance required from the wheel. The user concentrates on his specific requirements, while the maker concentrates on the performance characteristics of his wheels.

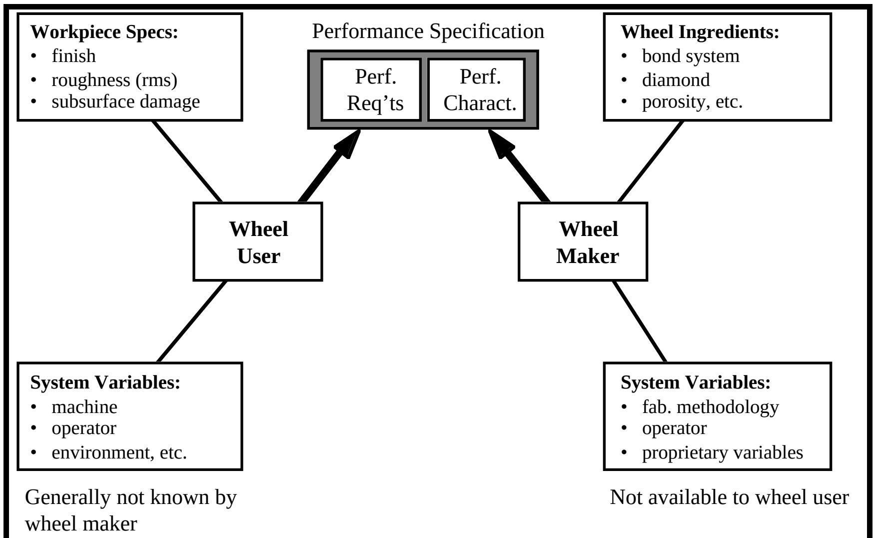

Figure 3. A performance specification offers an intermediate language with common terminology for both wheel users and wheel makers.

An important goal of this proposed set of tests is to be able to assess the likelihood that a given wheel will perform successfully for a given application. Thus, if measurements from two wheels are inter-compared, the relative performance characteristics of the two wheels could be estimated prior to actually using them on a grinding machine.

Key requirements for such a set of metrics to be useful are for the wheel user to be able to relate his specific system requirements to a required level of performance from a wheel, and for the wheel maker to be able to relate his wheels to a level of performance. If these requirements are met, then it becomes possible to perform wheel optimization tests without resorting to specific production machines, or referencing wheel ingredients. Also, since wheel performance information is independent of specific machine variables, these results can be transferred to a number of specific applications. The user's knowledge of the details of each application can discriminate among the different wheels. There might be several broad categories of metrics, ranging from all-inclusive empirical grindability assessments, to rigorous property measurements; these will be described in a later section.

Another important requirement is that testing equipment and procedures be available for measuring the performance characteristics of wheels. Satisfying this requirement is goal beyond the scope of this proposal, and will require input from a variety of industrial sources. Some possibilities for performing the testing will be suggested after a discussion of the possible formats for these metrics.

The development of purchasing specifications from wheel performance metrics

If it was demonstrated that a wheel user could discern the applicability of wheels based on off-line test results, then it would be a natural evolution to specify wheels based on these metrics. This situation has a number of advantages. First, the focus becomes one of performance instead of wheel ingredients. Second, the wheel maker does not have to continue to discuss proprietary wheel properties, but can focus on helping the user specify appropriate values for the performance metrics. The wheel maker can concentrate on meeting the requirements for the performance metrics, and is not tied to wheel evaluations on systems that are out of his control. The wheel maker can successfully deliver wheels that meet the performance metric requirement, but his level of responsibility will not be directly tied to the use or misuse of the wheels in a specific production environment.

The availability of objective assessments of wheel performance would offer a new tool for assessing and controlling the repeatability of wheels. Although, many wheel makers follow stringent procedures for providing repeatable wheels by controlling the quality of their ingredients, a set of performance metrics offers a bottom line test on quality control. This assessment of wheel performance repeatability offers a way of discerning the origins of a deficiency in a grinding operation. Thus if a user's production line begins to show poor results, one can refer to measurements of wheel metrics, and determine if the problem lies with the wheel or with other system variables.

Evolving from performance-based specifications to a Voluntary Product Standard

The concept of using performance metrics as a purchase specification becomes unworkable if the wheel maker encounters a different set of metrics from every customer. Conversely, the wheel user will have a tough time if every wheel maker presented their products according to a different set of metrics.

The solution to this lack of interchangeability among performance specifications lies in the formation of a *voluntary product standard*, where representatives from both the wheel users' and wheel makers' communities agree on a set of terminology, definitions, and test specifications. This standardized terminology would form the basis for the buying and selling of wheels. How each participant prioritizes the tests would depend entirely on their own applications and preferences, but would relate to others' use of the same terms and tests.

It is important to note that conformance to such a standard would be voluntary: hence the phrase *voluntary* product standard. Wheel makers who are very familiar with their customers' applications and the performance characteristics of their wheels may be able to provide reliable recommendations for wheels without the use of performance metrics. Likewise, a very small-quantity wheel user may not be sufficiently familiar with how performance metrics would relate to his applications, and would prefer to simply try a number of wheels. However, if properly formatted, it is likely that selecting wheels based on performance metrics will allow the user to focus less on the details of the wheel ingredients, and focus more on performance. Note that for the fine grinding of brittle materials, the sophistication and difficulty of this application may predicate the move to performance-based product standards.

Possible formats for a performance-based metrics for grinding wheels

There are several possible formats that might be appropriate as standards for specifying grinding wheels. Four general categories are listed in Fig. 4. The upper box refers to wheel ingredients, which really represents the type of format used today. Some aspects of wheel ingredients will probably always be specified: such as *diamond as the abrasive*, or perhaps the overall bond system. The next lower box indicates grindability tests. These are performance tests done on a machine sufficiently similar to one used in a particular application so that measured performance results, such as rms roughness, bear a relevance to the target application. Even if the measured numbers differ from those expected for the target application, the relative scoring of wheels could be used as a metric. An example of this could be the rms roughness measured after a standardized grinding operation on a well-characterized spherical generator (hopefully without major error sources). The relative performance of wheels on this machine using one or more standard work materials may relate to relatively large number of spherical generators.

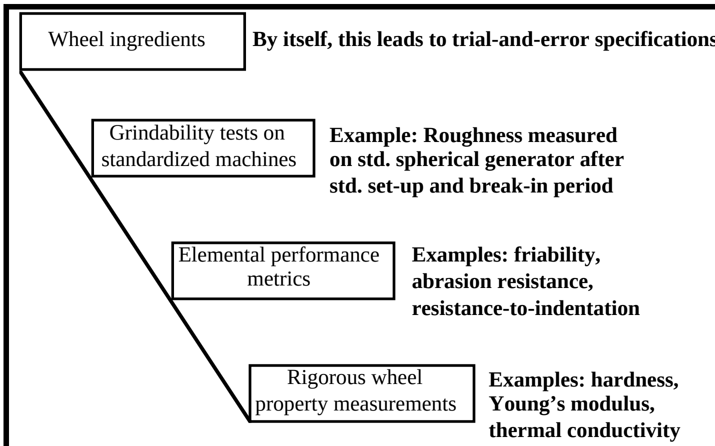

Figure 4. Several formats exist from which to formulate a wheel specification.

The third box in Fig. 4 indicates 'elemental performance metrics', which refers to well-specified tests of wheel characteristics that provide a detailed measure of the wheel's contribution to fundamental aspects of the overall grinding process. A key objective of metrics in this category is to relate to a limited number of specific physical mechanisms that are important in the grinding process. An example of this metric is a *thermal figure-of-merit*, which could be specified such that it is indicative of how the wheel's thermal properties transfer heat away from the grinding zone. Since issues such as geometry and testing methods would probably be included in this metric, it would not be a rigorous material property measurement. Another proposed elemental performance metric is *resistance-to-indentation*, which relates to the wheel's ability to deform in order to accommodate localized force disturbances [described in the Appendix]. A list of candidate metrics is shown in Figure 5.

- Resistance-to-indentation - grit scale
- Resistance-to-indentation - patch scale
- Grit protrusion height after dressing
- Grit protrusion height after controlled usage
- Width of protruding diamonds
- Roughness of bond after dressing
- Grit friability
- Bond friability
- Abrasion resistance - std work material
- Abrasion resistance - std dressing material
- Abrasion resistance - std truing material
- Thermal figure-of-merit
- Corrosion resistance
- Porosity

Figure 5. Candidates for elemental performance metrics.

A further category of potential metrics for use in specifying grinding wheels are rigorously-measured *thermo-mechanical properties*. These include parameters such as thermal conductivity, thermal diffusivity, specific heat, Young's modulus, chemical composition, density, pore structure, etc. These parameters are of a more fundamental nature than the performance metrics described above. Clearly, there exists a link between all of these property terms and all of the performance characteristics of the wheel. The connection, however, between property values and the distinction between good and bad wheels is the most remote and difficult of the types of metrics that have been discussed.

Hybrid specification

Ideally, if a set of objective elemental performance metrics existed that were sensitive to all relevant performance requirements of the wheels, then this alone would be sufficient to specify the wheel and its relationship to user applications. Also, these tests would be sensitive to variations in all relevant wheel ingredients. However, until such a set is identified, it is likely that some combination of ingredients, grindability, and performance metrics will be necessary. It may be desirable to specify some set of ingredients, because there are only a few limited choices: for example diamond friability might have a specific performance requirement, but if there are a limited number of types of diamonds for the size of interest, then it seems reasonable to specify the diamond directly. Thus, a hybrid version of a specification might have call-outs from multiple levels in Figure 4.

Proposal for future work and collaboration

Although the benefits of performance-based specifications and standards for fine grinding wheels are clear, the path to defining and enacting them requires much work. One path is to begin with a small number of interested wheel users and wheel makers and strive to define a set of critical performance metrics. From this, a testing methodology would be proposed, and performance testing equipment identified. Tests could be performed on small sample quantities of wheels that are already used in production, and thus have a track record for comparing with the tests. Success would be identified when a set of off-line tests could successfully distinguish between ‘good’ and ‘poor’ wheels. A sound testing methodology, combined with a physical understanding of the nature of the test, would lead to a strategy for improving both grinding wheels and the grinding process.

We propose that a working group be formed, perhaps under the joint sponsorship of the American Society for Precision Engineering, the American Precision Optics Manufacturers Association and the Industrial Diamond Association, to outline a strategy for investigating this proposal. Because the ultimate goal of this activity would be to improve the methodology of buying and selling grinding wheels, both users and makers of wheels should be well represented.

Acknowledgments

The authors would like to express their appreciation to the Center for Optics Manufacturing (Rochester, NY) and the American Precision Optics Manufacturers Association for continued collaboration in precision fine grinding. In addition, we would like to thank Fred Gray and members of the Industrial Diamond Association for encouraging discussions on the subject of standards for grinding wheels.

Notes

[1] Taylor, J. S., Piscotty, M. A., Blaedel, K. L., and Gray, F. A., "Working With the Superabrasives Industry to Optimize Tooling for Grinding Brittle Materials", **Proc. of the 1996 Spring Topical Meeting on Precision Grinding of Brittle Materials**, vol. 13, American Society for Precision Engineering, 95-102 (1996).

[2] An exception to this is the association of a *hardness* grade to a wheel. This usually refers to a company-specific test for abrasion resistance of the wheel. It also has implications regarding the traditional mechanical concepts of hardness and Young’s modulus.

[3] See, for example: **ISO 6168: 1980** "Abrasive Products -- Diamond or cubic boron nitride grinding wheels -- Dimensions"; **ANSI B74.3: 1993** "Specifications for shapes and sizes of diamond or CBN abrasive products"; **ANSI B74.13: 1982 (R 1993)** "Markings for identifying grinding wheels and other bonded abrasives".

[4] Gray, F., “A Look at the Superabrasives Industry Today”, **Finer Points**, vol. 7 no. 4, 1995, pp. 8-10.
[5] It is worth noting that some momentum is growing for some types of fine diamond wheels, as the use of ceramic components in transportation and propulsion systems increases. Progress in the use of ceramics in areas such as propulsion and transportation systems is reported in the **Ceramic Technology Newsletter**, published by Oak Ridge National Laboratory and within a number of conference proceedings such as **Proceedings of the International Conference on Machining of Advanced Materials**, July 20-22, 1993, Gaithersburg, MD, S. Jahanmir editor, NIST Special Publication 847.
[6] Development information is becoming increasingly available to both makers and users of fine diamond wheels, in that a number of universities and laboratories are investigating equipment and material removal processes dedicated to brittle materials. For more information, please contact: Lawrence Livermore National Laboratory (John S. Taylor at 510-423-8227), North Carolina State University (Tom Dow at 919-515-3096), the National Institute for Standards and Technology (Chris Evans at 301-275-3484), or the Center for Optics Manufacturing (Harvey Pollicove at 716-275-2762). Other relevant institutions can be identified by examining the conference proceedings of the American Society for Precision Engineering, the *Annals of the CIRP*, or conference proceeding of the Society of Manufacturing Engineers.
[7] At least one grinding wheel manufacturer has constructed a major laboratory facility for evaluating wheel performance on user-specified production equipment.

Appendix
Paper presented at the
1996 Spring Topical Meeting on Precision Grinding
American Society for Precision Engineering
May 1-3, 1996 Annapolis, Maryland

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

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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.

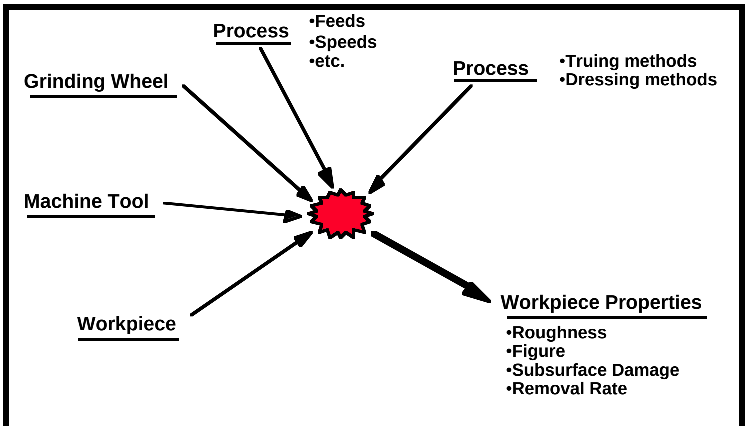

Figure 1. The system view of grinding encompasses all input variables that affect workpiece properties and cost.

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

* This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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).

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.

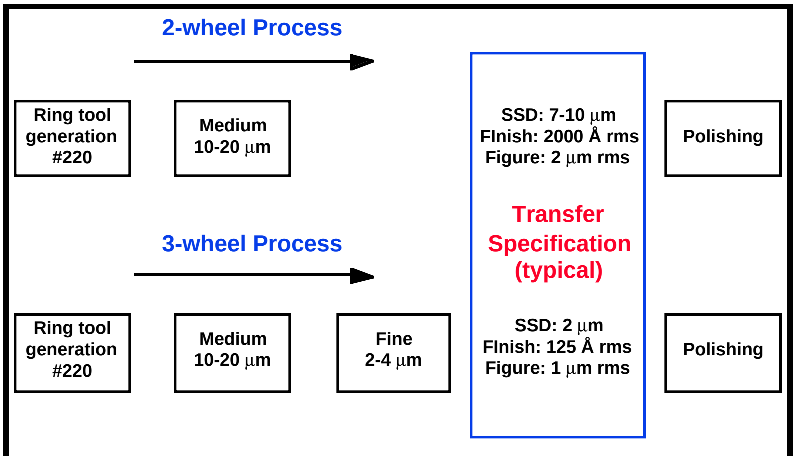

Figure 2. A number of input variables to the material removal process determine the output features of the workpiece, including cost.

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

Table 1. Manufacturers of bound diamond tooling with diamond sizes ≤ 20 μm.

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 Fillipone	AZ	602-966-9311	602-966-2273
Diagrind, 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

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 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 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.

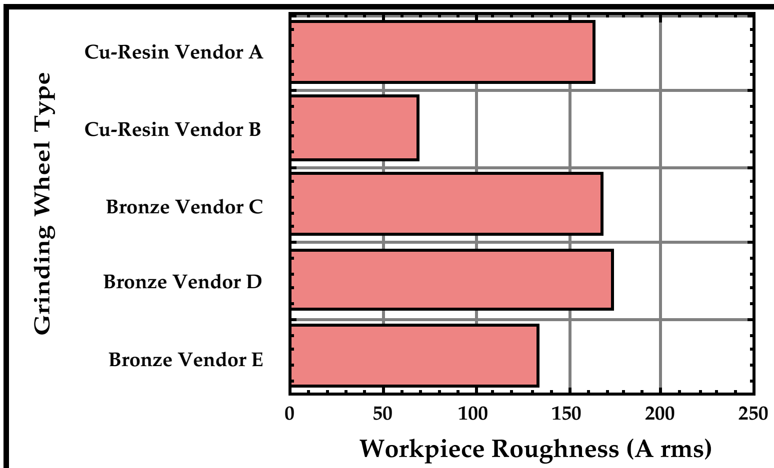

Figure 3. Comparison of roughness values (Zygo NewView 20x) achieved with commercial wheels; 2-4 μm wheels.

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 grindabilty ***G*** represents a figure-of-merit for the selection of grinding wheels.

(a)

$$G^2_{user} = a_1(rms)^2 + a_2(SSD)^2 + a_3(figure)^2 + a_4(g-ratio)^2 + a_5(feedrate)^2 + a_6(effort)^2 + a_7(cost)^2$$

(b)

$$G^2_{maker} = b_1(diamond)^2 + b_2(bond)^2 + b_3(filler)^2 + b_4(porosity)^2 + b_5(concentration)^2 + b_6(procedure)^2 + b_7(cost)^2$$

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.

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.

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^2_{maker} and G^2_{user} 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

Composite Figure-of-Merit

$$G^2 = \sum_i a_i (FOM_i)^2$$

FOM_i = elemental performance metrics

a_i = application specific weighting coefficient

$$G^2 = a_1(hardness)^2 + a_2(friability)^2 + a_3(clearance)^2 + a_4(protrusion)^2 + a_5(temp stability)^2 + a_6(dressability)^2 + a_7(self sharpening)^2 + a_8(heat transfer)^2 + a_9(grit shape)^2 + a_{10}(chem stability)^2$$

Figure 5. Proposed performance figures-of-merit can bridge between user requirements and proprietary wheel information.

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.

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 indentor 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 indentor, 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 indentor. The ability of the wheel to accommodate waviness on the wheel due to truing errors, might ideally be tested by using a large-radius indentor.

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.

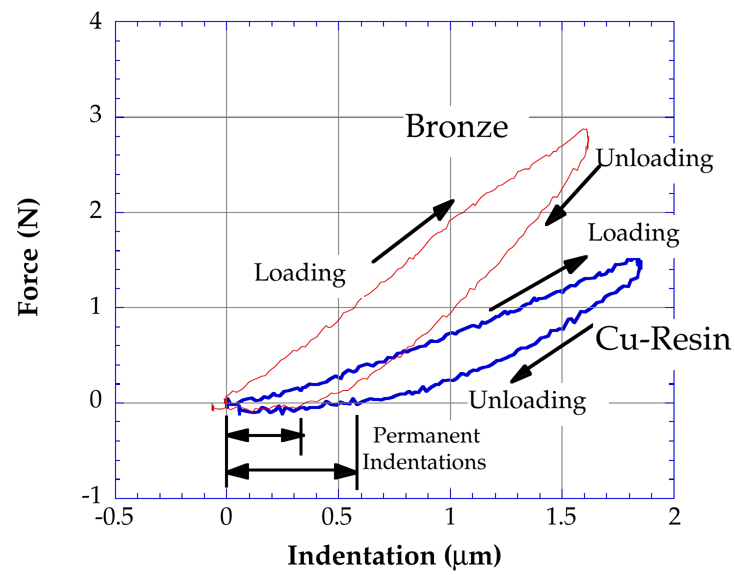

Figure 6. An example of a 'hardness' test that compares resistance to indentation between a Cu-resin-bond wheel and a bronze-bond wheel.

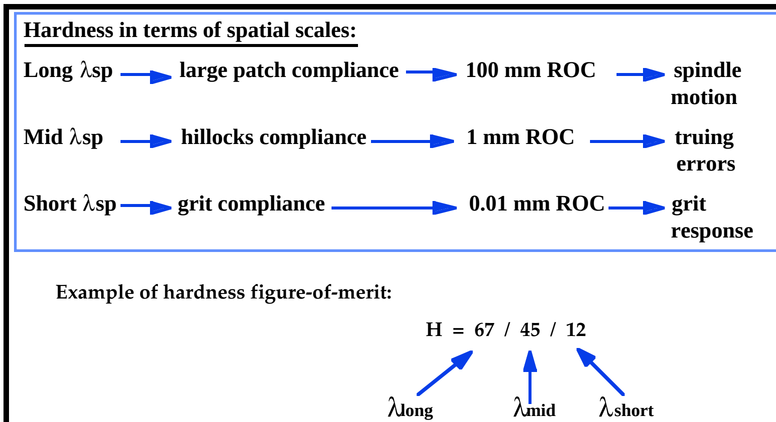

Figure 7. Several scale lengths may be necessary to represent a grinding wheel's resistance to indentation.

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

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Notes

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[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.

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