Performance Study of Scepter™ Metal Bond Diamond Grinding Wheel

Presented at the

Precision Grinding and Grinding with Superabrasives Conference
Session VI-Advances in Diamond Superabrasive Grinding Wheel Technology
Chicago, Illinois
June 17, 1999

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1. Introduction

Advanced ceramics are attractive for many applications in the transportation, energy, military, and industrial markets because they possess properties of high-temperature durability, corrosion resistance, strength, hardness, stiffness, and wear resistance. Unfortunately, these same properties make advanced ceramics more difficult to machine than traditional materials. The reliability and manufacturing costs of advanced ceramic components are significant concerns that must be overcome. Nevertheless, the use of advanced ceramic materials is expected to increase dramatically in new transportation systems in response to more stringent energy conservation and pollution reduction requirements.

A survey of all Norton industrial ceramic businesses showed that typical machining costs for advanced ceramic components range from 20% - 70% of the total cost of manufacturing depending on product requirements[1]. Thus, machining cost is a major impediment to widespread use of ceramic engine components. The reasons for the high machining costs are: (1) machining is both capital and labor intensive, (2) expensive diamond abrasive is consumed, and (3) production rates are relatively low[2]. The requirement for frequent wheel dressing when grinding ceramics has also been identified as a significant factor in abrasive cost.

Achieving consistently high quality and reliability in ceramic components is just as important as reducing machining costs. Quality is measured not only in terms of appearance. dimensional accuracy. and surface texture, but also by mechanical properties. Generally, ceramics are much more brittle than metals. and have lower fracture toughness. They are therefore more susceptible to failure due to subsurface cracks and internal flaws than more ductile materials. As advanced ceramic materials have improved, machining induced damage has become a major concern. Relatively economical cut rates can be accomplished by grinding in the brittle mode of material removal. However. for some applications it is necessary to change to finer-grit-size wheels and much lower removal rates in order to work in the ductile mode and minimize subsurface damage.

The U.S. Department of Energy, Office of Transportation Technologies has sponsored research with the objective of improving reliability and reducing the manufacturing cost ofceramic components. The goal of the Ceramic Technology for Advanced Heat Engines Program (I 984-1996), managed by Oak Ridge National Laboratory (ORNL). was to develop highly reliable and cost-effective structural ceramics for advanced heat engine applications such as automotive gas turbine, piston, and diesel engines. In recognition of the importance of machining to commercializing advanced ceramics, the Cost-Effective Ceramic Machining (CECM) initiative was established in 1991 as part of this program Ceramic machining, primarily with a diamond abrasive wheel, is a major cost factor in the manufacture of advanced ceramic components. The performance of the wheel significantly influences grinding costs. In addition, the quality of the grinding operation greatly affects ceramic surface integrity, tolerance. and manufacturing yield.

The driving force behind the new, commercially available, Scepter™ Diamond Grinding Wheels was Norton Company's tive-year cooperative project with the US Department of Energy (DOE). A multi-phase Project entitled *Innovative Grinding Wheel Design for Cost-Effective* ***Machining of Advanced Ceramics*** was performed by Norton Company in response to Request for Proposal (RFP) No. SM037-87, and was managed under the CECM initiative. The project's objective focused on improving the reliability of advanced ceramics and reducing their manufacturing cost. The project emphasized cylindrical grinding of silicon nitride and other advanced ceramics. The material and application selection are consistent with the majority oftransportation component needs. Innovative wheel compositions that were optimized for

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cylindrical grinding of advanced ceramics can be optimized for other machining operations such as centerless, surface, and ID grinding[3]. This study discuss& the goals, commercialization plans, phased development, scale-up, testing, and external verification of performance of the innovative grinding wheel that evolved from the project.

2 . Background

Technical goals

The three principal bond types for abrasive wheels can be classified as resin, vitrified, and metal. In the infancy of advanced ceramics, resin-bonded diamond grinding wheels were good starting points because they provided quality surfaces with good part strength. At that time, vitrified and metal bonded products required high specific grinding energy and resulted in poor part strength due to surface microfractures. Even though resin wheels possess poor wheel wear characteristics and require frequent dressing, they still remain the all-purpose wheels for grinding ceramics.

Vitrified wheels were soon developed to provide better wheel life. These vitrified wheels are toward the soft side in the range of available vitrified wheels, and they provide an improvement over resin wheels. However, they need to be handled with care due to their lower bond strength and brittle nature.

Conventional metal bonded wheels are exceptionally durable and consume more power to grind fine grain ceramics. They typically require continual dressing to remove worn abrasives and to expose sharp diamonds. The advantages of metal bonds are their increased bond strength and higher wheel speed capabilities. High-speed grinding has shown significant potential for ceramics grinding'.

It was initially decided to focus efforts on developing a metal-bonded diamond wheel for the CECM Program. Metal-bonded wheels demonstrated the most favorable attributes of all current bond structures, as described above. Specifically, the experimental metal bonds were designed to give intermediate grinding action between standard resin and metal bonds, Several variations were developed to meet this specification.

Phase I Screening Studies

The objectives of the Phase I program were to define requirements, design, develop and evaluate a next-generation grinding wheel for cost-effective cylindrical grinding of advanced ceramics.

In an effort to reduce the number of potential bonds, an initial grinding test was done on three types of material representative of those available in the market. Three materials manufactured by Saint Gobain Industrial Ceramics were used to meet the market applicability and performance criteria- NC-520 SiAlON, NCX-5102-HIP'ed Si_3N_4, and AZ67H-20%ZTA (zirconia-toughened alumina). The wheel evaluations were performed at the Norton World Grinding Technology Center on an instrumented CNC cylindrical grinder in both plunge and traverse test conditions. One experimental wheel successfully ground all three types of advanced ceramics for an extended time without the need for wheel dressing. This bond later became the heart of the Scepter™ Diamond Wheel.

Results of Phase I

- The experimental wheel required as much as 30% less spindle power during the grinding tests of NC-520 than the standard 100 concentration resin-bonded diamond wheel, which is typically used in this application.

- The wheel wear was an order of magnitude lower than that of the resin-bonded wheel; this significantly reduces ceramic grinding costs through a reduced number of truing operations, dressing operations, and wheel changes.
- The results indicated that the experimental wheel did not create unusual or excessive machining damage compared to the standard resin-bonded products. The surface qualities of the specimens ground with the experimental wheel were shown to be of comparable quality to those ground with the resin-bonded wheel. This was demonstrated through optical examination, C-ring compression tests, and traverse ground SiAlON MOR bars.

3. Phase II Wheel Development, Scale-Up, and Internal Testing

Development and Scale-Up

The objective of the development and scale-up task was to increase the Scepter™ Diamond Wheel from 203mm (8 in) to diameter to 393 mm. Manufacturability, reliability, and safety were the key focus to maintain a consistent performing wheel.

In the initial testing it was determined that high speed grinding was necessary for this wheel to optimally perform grinding of ceramics. The Scepter™ Diamond Wheel's segmental design was chosen to minimize tangential stresses associated with continuous-rim wheels at high speeds. Manufacturing the segments to near-net-shape reduced cost by avoiding laborious machining of the segments by grinding. It also allowed for inside curvatures and angles to be matched so that fit-up between mating segments and the core would be acceptable.

Description Of In-House Testing

The testing for Phase II was performed at Norton Company's World Grinding Technology Center on a Model S40 Studer CNC grinder. This testing investigated the grinding characteristics of the Scepter™ Diamond Wheel compared to a vitrified-bonded (SD320-N6V10) and resin-bonded wheel (SD320-R4BX619C). Testing was performed at three speeds: 32m/s (6252 SFPM), 56 m/s (11,000 SFPM), and 80m/s (15750 SFPM). The resin wheel was tested at all speeds. while the vitrified was only tested at 32m/s.

Tests were performed in cylindrical OD plunge mode in grinding NT551 silicon nitride rods. To preserve the best stiffness of work material during grinding the 88.9 mm (3.5in.) samples were held in a chuck with approximately 31 mm (1.22 in) exposed for grinding. Each set of plunge grind tests started from the far end of each rod. First the wheel made a 6.35 mm (1/4 in) wide and 3.18 mm (1/8 in.) deep (radial depth) plunge. The work rpm was then readjusted to compensate for the loss of work speed due to reduced work diameter. Two more similar plunges were performed at the same location to reduce the work diameter from 25.4 mm (1.00 in) to 6.35 mm (1/4 in). The wheel was then laterally moved 6.35 mm (1/4 in) closer to the chuck to perform the next three plunges. Four lateral movements were performed on the same side of the sample before reversing the sample. A total of 24 grinds were performed on each sample. Figure I shows the various work pieces that were ground during in-house testing.

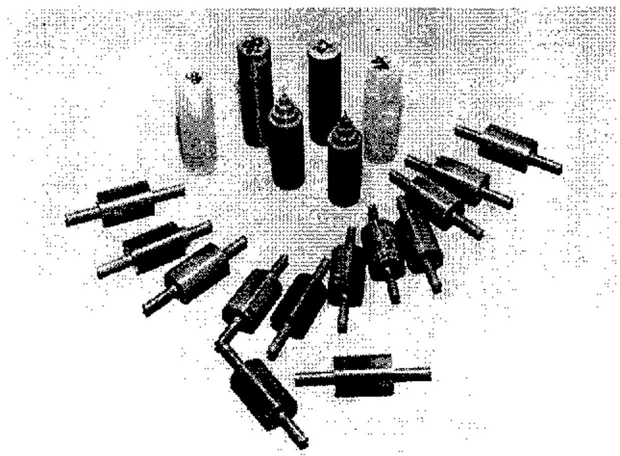

Figure 1. Various test specimens produced during in-house tests.

Results Of In-House Grinding Test

The Scepter™ Diamond Wheel reached a material removal rate of 41.3 mm^3/s/mm (4.4 in.^{3}/min.in) at 80m/s wheel speed without showing measurable wheel wear or surface-finish deterioration on the ground parts. This is a significant improvement in grinding productivity and reduction of machining cost for the advanced ceramics market.

At each of the material removal rates (from 8.3 mm^3/s/mm to 41.3 mm^3/s/mm), the Scepter™ Diamond Wheel demonstrated consistent grinding power consumption and surface finish in grinding NT551 silicon nitride samples even after extensive plunge grinds.

At 32m/s speed, the Scepter™ Diamond Wheel had slightly greater power consumption than a resin-bonded wheel, but at 80m/s the Scepter™ wheel had power consumption comparable to the resin wheel.

The Scepter™ Diamond Wheel demonstrated superior wheel life compared to the resin and vitrified-bonded wheels. Figure 2 shows the performance differences, as depicted by G-ratios, among the three different types of wheels after twelve plunge grinds. The Scepter™ Diamond Wheel was superior to both the resin wheel and vitrified wheel at all material removal rates.

Overall, these results indicate that a large benefit can be realized by the ceramics industry when using the innovative ScepterTM Diamond Wheel. It was observed that this metal-bonded diamond wheel doesn't require constant and frequent dressing, characteristic of standard metal-bonded diamond wheels. The ScepterTM Diamond Wheel demonstrated a free cutting ability throughout the entire life of the wheel.

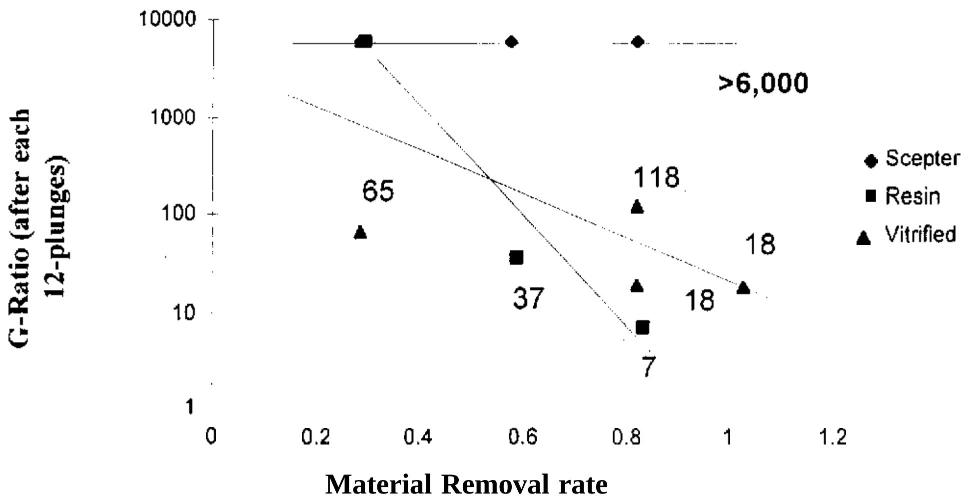

Figure 2. G-ratio vs material removal rate at 32 m/s grinding speed.

4. Results of Independent External verification of wheel performance

During 1997. independent "beta" testing of the Scepter™ Diamond Wheel was conducted at three locations: the Caterpillar Technical Center, Chand Kare Technical Ceramics. and the Eaton Manufacturing Technology Center. A full discussion of test results is beyond the scope of this paper. but may be found in the previously discussed Phase II report issued by Norton Company'.

Caterpillar Technical Center – Peoria, Illinois

The grinding test was done at two feed rates on both Norton Advanced Ceramics' NT551 silicon nitride and Caterpillar-supplied magnesia partially stabilized zirconia. Mg-PSZ.

Test Procedure

Caterpillar's program consisted of two parts. The first part used Mg-PSZ rods, 6.5 mm in diameter by 70-mm-long, to simulate a centerless grinding operation used to manufacture zirconia fuel injector components. The second part used NAC NT551 **silicon** nitride rods, approximately 25.4 mm in diameter by 90-mm-long, to simulate the centerless grinding of right circular cylinder structural components. such as valve guides or valve seats.

The centerless grinding was done on a Liokoping Centerless grinder, using Hocut 763-MY Undyed, a water-based coolant (5 percent by volume coolant). The Scepter™ Diamond Wheel (specification: - I A ISA 15.5-in. x 0.5.in. x 9.0002-in. [D-2MXL1994-.25] was compared to a 320 grit, 100 concentration. vitrified-bond diamond wheel (DIA 1, 16-in. x OS-in. x9-k).

The maximum taper on the grinding wheel controlled the maximum depth-of-cut for the Liokoping. For this trial, a 0.1mm taper was placed on both the Scepter™ Diamond Wheel and vitrified-bond grinding wheels. This taper allowed a maximum stock removal of 0.1 mm from the diameter, per pass. Since the taper on the grinding wheel fixed the depth of cut, the evaluation consisted of centerless grinding both the zirconia and silicon nitride specimens at two constant thrufeed rates (fast and slow).

After each set of specimens was machined, the wheel wear was measured. The G-ratio was calculated for each grinding condition, In addition, the number of times the grinding wheel required dressing during the grinding of a group of specimens was noted.

After machining, the surfaces of both the zirconia and silicon nitride rods were quantified using 3-D surface analysis and scanning electron microscopy techniques. The residual stress of the silicon nitride surfaces after machining was determined using X-ray techniques. Finally, the effect of machining on the mechanical properties of the zirconia rods was determined by breaking the machined rods using 4-point bending techniques conforming to Military Standard 1942A.

Conclusions from the Caterpillar Test:

- The Scepter™ Diamond Wheel demonstrated lower wheel wear than the vitrified-bonded wheel when centerless grinding either Mg-PSZ or NT 551 rods at either thrufeed rate. Increasing the thrufeed rate increased the difference in G-ratios between the two wheels because of the significantly higher wheel wear of the vitrified-bonded wheel.
- When machining silicon nitride at the higher thrufeed rates (7.3 mm/s), the vitrified-bonded wheel started to break down producing rougher surface finishes with higher residual stresses than the Scepter™ Diamond Wheel.
- The flexural data on zirconia suggest that the Scepter™ Diamond Wheel caused less grinding damage than the vitrified-bonded wheel. As determined by fractography, the critical flaws that caused failure in zirconia rods machined using the Scepter™ Diamond Wheel were volume flaws (i.e.. porosity), resulting in a higher Weibull modulus. However, the critical flaws that caused failure for zirconia machined with the vitrified-bonded wheel were both volume and surface flaws (i.e., pits in the machining grooves). These two failure modes caused a wider distribution of flexure strengths, and lower Weibull modulus, because the surface flaws caused failures at lower loads than the volume flaws. However, the average bend strength of the Mg-PSZ rods did not appear to be affected by the grinding wheel.
- The truing and dressing of the Scepter™ Diamond Wheel was no more difficult than the truing and dressing of the vitrified-bonded wheel. During machining, the Scepter™ Diamond Wheel required less dressing than the vitrified-bonded wheel, especially at the higher thrufeeds.

Chand Kare Technical Ceramics – Worcester. MA

The grinding tests were done on NT551 Si_3N_4 rods (supplied by Notion) under external cylindrical grinding mode.

Test Procedure

Chand Kare evaluated the Norton Scepter™ Diamond Wheel (1 A ISA 400mm x ½ x 5.002 Specification: D-2MXL1994-.250) along with a standard resin-bonded wheel (Norton SD320R75B99E.16 inch diameter, ½ inch wide). Chand Kare evaluated grinding power, specific energy. surface roughness, wheel wear, and wheel truing time. Grinding tests were performed under external cylindrical grinding mode using an OD/ID grinder. Center holes were drilled on both ends of the rods and the rods were held between centers.

Conclusions from the Chand Kare Test

- Grinding with the Scepter™ Diamond Wheel required significantly lower specific energy than the resin-bond wheel tested.
- The Scepter™ Diamond Wheel consumed much lower specific energy than the resin-bond wheel for all tests.
- The Scepter™ Diamond Wheel resulted in more consistent specific energy than the resin-bonded wheel.
- No difference was observed in surface roughness between the parts ground using the Scepter™ Diamond Wheel and parts ground using the resin-bonded wheel.
- The two wheels required basically the same truing time.
- Both wheels have similar form holding capability under the test conditions.
- The results also showed that the Scepter™ Diamond Wheel exhibited slightly higher wheel wear than the resin-bonded wheel. However, the difference was not statistically significant. The conclusion is that the two wheels have similar wear within the test conditions.

Eaton Manufacturing Technology Center – Cleveland, OH

Eaton evaluated the Scepter™ Diamond Wheel at speeds up to 18,000 SFPM (91 m/s). The test included an evaluation of the metal-bonded wheel by Electrocontact Discharge Dressing (EDD). The NT55 I workpieces were received for testing in the "as-fired" condition. Prior to testing, the workpieces were ground to a dimension of 1.000 inches (25.4 mm) using the 240-grit resin wheel. The workpiece was held in a six-jaw chuck and grinding was always done as close to the jaws as possible to maintain constant workpiece stiffness. A contact width of 0.400 inches was kept constant and the wheel was plunged to take the workpiece to a nominal diameter of 0.25 inches. The workpiece was indexed 0.500 inches after a plunge grind and the subsequent plunge made. Radial wheel wear was determined by measuring the step height differences between the ground and unground portion of the wheel face. The small wheel wear values were measured on a plunge-ground reference sample using an optical comparator.

Test Procedure

The two wheels selected for this study were the Scepter™ Diamond Wheel, IA ISA 400mm x ½ x 5.0002 (specification: D-2MXL1994-.250), and a 12-inch-diameter, 240 grit polyimide resin-bonded diamond wheel (D240-100-UI841). Both wheels were approximately 0.5 inches wide. A modified Weldon 1632 OD grinder was used to plunge grind Norton NT55 I silicon nitride cylindrical specimens.

Grinding test conditions were:

- Wheel speeds – 6,000; 12,000; and 18.000 SFPM (30.5. 61, and 91 m/s)
- Material removal rates, (MRR) – 0. I, 0.5, and I .O in^3/min/in. (1.08, 5.4, and IO.8 mm^3/s/mm)
- Coolant-water-soluble oil.

Truing was done after mounting each wheel and when necessary to remove any wheel wear. Dressing was done before each test but not in between passes for a given test condition. The resin wheel was trued and dressed using an Eaton-developed method for resin-bonded wheels. Two different dressing methods were evaluated on the Scepter™ Diamond Wheel. The first method was the Norton specified method using an SG wheel followed by sticking. The other method was Eaton's Electrocontact Discharge Dressing (EDD) system.

Conclusions from the Eaton Test

- In general, the conventionally dressed Scepter™ Diamond Wheel cut with comparable or lower normal force and power, achieved a better surface finish, and had less wear than the coarser resin-bonded wheel.
- For both wheels, increasing the wheel speed reduced the amount of wear. At the middle material removal rate using the resin wheel, wear was reduced by more than a factor of two by increasing wheel speed from 6,000 to 18,000 SFPM. The Scepter™ Diamond Wheel was much less sensitive to wheel speed effects in reducing wear than the resin.
- The EDD dressed wheel resulted in lower specific grinding energy compared to the conventionally dressed wheel. However, the EDD wheel also suffered from severe wheel wear, bond smearing, and grit pullout. It does not appear that this bond type is readily adaptable to an aggressive electrocontact-based dressing system such as EDD.

5. Results of Final Beta Testing at Oak Ridge National Laboratory (ORNL)

After the external verification of wheel performance, a final series of tests was performed at the Oak Ridge National Laboratory's Machining and Inspection Research User Center to investigate the long-term behavior of the wheel while grinding advanced ceramic materials under aggressive conditions. Tests were conducted jointly by Norton and ORNL personnel under the High Temperature Materials Laboratory User Program." Norton Company was particularly interested in demonstrating that the segmental design of the wheel would provide consistent performance over the life of the wheel in terms of gradients within the segments.

Description of Tests

Long-term grinding tests were performed using the Weldon Model AGN5 cylindrical grinder shown in Figure 3(a). The tests were conducted in approximately 20-hour stages, with a dimensional inspection of the wheel profile at the end of each 20-hour period.

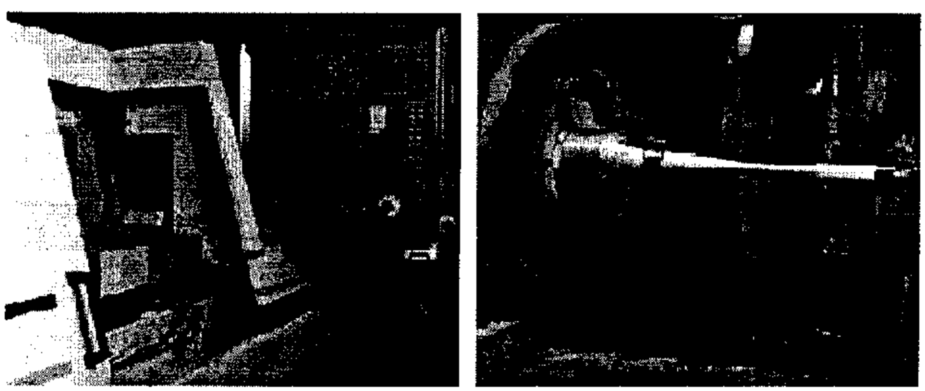

Figure 3. (a) The Weldon Model AGN5 Cylindrical Grinder at the ORNL Machining and Inspection Research User Center. (b)Silicon nitride button head tensile specimens being profile-ground between centers on the Weldon cylindrical grinder.

Cylindrical grinding of silicon nitride button-head tensile rod specimens was selected as a particularly demanding application because it includes both straight OD-plunge grinding and OD-contour grinding.

** Research sponsored by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies, as part of the High Temperature Materials Laboratory User Program, Oak Ridge National Laboratory, managed by Lockheed Martin Energy Research Corporation for the U.S. Department of Energy under contract number DE-AC05-96OR22464.

This type of grinding operation taxes both the flat sections and the leading edge of the wheel. Because the test parts are real-world components with complex geometry rather than simple cylindrical shapes, the resulting data are much more difficult to analyze. For example, wheel wear and grinding ratio measurements involved the analysis of complex profiles rather than measurement of simple steps. The composite material removal rate (MRR) is also difficult to compute because the grinding cycle involves complex paths, dwell times, direction reversals, and changes in traverse rate. Although an attempt was

Table 1. ORNL Experimental Parameters.

Wheel Description	Norton Scepter™ 1A1SA; Norton Number: D-2MXL1994-.25	
Wheel Size	16 in. diameter X 0.5 in. wide X 5.0002 bore	
Workpiece Material	Allied Signal GS-44 Si_3N_4 (high-performance silicon nitride)	
Spindle Speed	16000 SFPM (3820 RPM)	
Typical conditions during plunge grinding mode	In-feed rate: Up to 2.0 inch/minute over 0.375” width (0.94 in’ / min MRR in GS-44 Si_3N_4)	
Typical conditions during profile grinding mode	Straight path: 25 in./min. 0.001 in. depth of grind	Contour path: 4 in./min. 0.001 in. depth of grind
Coolant	Type: Milacron Cimtech™ 500, approximately 20:1	
	Flow rate: Approximately 16 gal./min	
Truing Procedure (using hydraulic rotary truing device)	Truing interval:	At initial setup only
	Truing wheel speed:	2400 RPM
	Grinding wheel speed:	1000 RPM
	In-feed:	0.0002” per pass
	Traverse rate	5 inches per minute
	Roll type	Beck 4” diameter roll #SDW10042-1 with 0.125” corner radius.
Dressing Procedure (using Norton 38A220-HVBE dressing stick)	Stick dress after initial truing, and then only as needed	

made to analyze and present data for G-ratios, MRR, etc., many of the results of this test are qualitative Setup of the specimens on the Weldon grinder is shown in Figure 3(b).

The experimental parameters are shown in Table 1. During the course of the experiment, force, power, and spindle vibration were monitored periodically using Labview™-based instrumentation. Part roundness. size and surface finish were also monitored.

One of the most important facets of the test was the determination of grinding ratios (volume of workpiece material removed divided by the change in volume of wheel). The wheel exhibited an extremely low wear rate throughout the tests, which made accurate calculation of G-ratios difficult. The parts were weighed at the beginning and end of each grinding operation. Knowing the density of the workpiece, the volume of material removed during the test could be easily calculated. The profile of the grinding wheel was measured on a very accurate coordinate measuring machine (CMM) at the beginning of the test, and approximately every twenty hours thereafter. The differences in profile geometry were used to calculate the volume of abrasive material removed from the wheel. **Typical wheel** profile charts are shown in Figure 4. An attempt was made to calculate the G-ratio from these measurements. Results calculated after 40 and 60 hours 3110 and 3500, respectively. **Due** to difficulties in measuring the wheel profile, measurement uncertainty was a significant concern. For this reason, results are not presented for

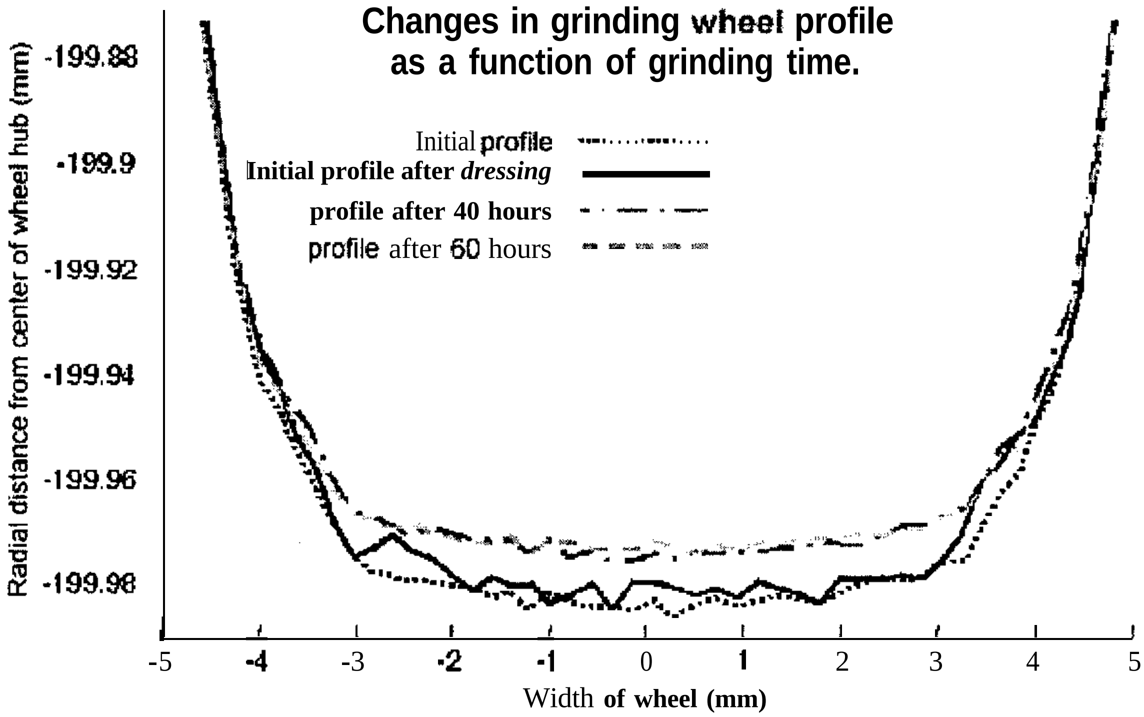

Figure 4. Changes in grinding wheel profile due to wear, as measured on a coordinate measuring machine.

the 20 and SO-hour measurements, For the SO-hour measurement, the measured wheel wear was less than the measurement uncertainty of the CMM. The measurement indicated (erroneously) that the wheel cross-section actually ***increased*** in size between the 60 and the SO-hour measurement. Such results indicate the need for improved techniques for measuring wheel wear in a laboratory environment.

At the end of approximately 80 hours of grinding, the wheel was sent back to Norton Company for non-destructive evaluation of the wheel's condition. No abnormalities were detected. Because the wheel wear was extremely low up to this point, approximately 0.100 inch of abrasive material was deliberately removed from the wheel at Norton in order to evaluate consistency of wheel performance throughout the life of the abrasive. The wheel was then returned to ORNL for further testing.

Subsequent testing of the wheel consisted of approximately 10 hours of plunge grinding into Si_3N_4 specimens at in-feed rates of up to 2.0 inches per minute. This corresponded to a material removal rate of approximately 2.5 in^3/in of wheel width. Measured values for spindle horsepower as a function of in-feed rate are shown in Figure 5.

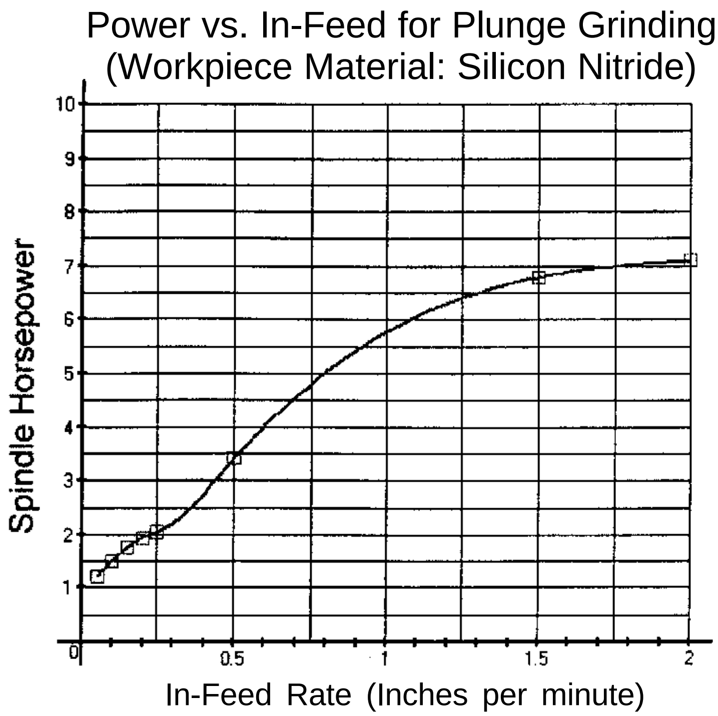

Figure 5. Spindle power as a function of in-feed rate.

Conclusions from the ORNL tests

- The wheel performed well throughout the tests, needing only occasional dressing.
- The wheel appears to have excellent form-holding characteristics.
- The calculated grinding ratios were consistently very high. (Some measurements yielded results as high as 8,000 on silicon nitride. However, accurate measurements were very difficult to achieve because of the extremely low wheel wear.)
- Part geometry and surface finish were at least as good as we typically achieve with vitrified bond diamond wheels.

6. Commercialization Plans

The design and performance goals for the Scepter™ Diamond Wheel were met, and it is now commercially available from Norton Company. Extensive testing has demonstrated that the wheel's capability and performance in grinding a variety of ceramics surpasses that of both vitrified and resin bonded wheels, and that wheel life over resin counterparts is greatly extended. Because of these demonstrated advantages, Norton Company believes that the market will embrace the wheel as the "wheel of choice" for grinding engineered ceramics.

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