New Technology in Metalworking Fluids and Grinding Wheels Achieves Tenfold Improvement in Grinding Performance

Presented at the
Coolants/Lubricants for Metal Cutting and Grinding Conference

Session 5: Optimizing Fluid Interaction in Cutting and Grinding Systems

The Ambassador West Hotel
Chicago, Illinois
June 7, 2000

M. K. Krueger*, S. C. Yoon, D.Gong – Milacron, Inc.

S. B. McSpadden Jr.*, L. J. O'Rourke,
R. J. Parten – Oak Ridge National Laboratory

(*Co-presenters)

New Technology in Metalworking Fluids and Grinding Wheels Achieves Tenfold Improvement in Grinding Performance

Abstract

Metal manufacturing industries have a growing interest in finding economical ways to improve grinding productivity, part quality, and production cost. Our study extensively investigated the effects of the types of grinding wheels, grinding fluids, and their different combinations on grinding ratio (G-ratio), specific energy (U), grinding efficiency (E), and surface roughness (R_a) of 52100 steel ground parts for a wide range of specific material removal rates. As a result of this study the following findings were made:

The specific material removal rate (Q') can be increased by more than 100 percent by using sol-gel wheels with metalworking fluids containing a high concentration of extreme pressure (EP) lubricants, instead of conventional aluminum oxide wheels with non-EP-containing fluids. The sol-gel grinding wheel generates an eight to ten times higher G-ratio than a traditional aluminum oxide wheel. Metalworking fluids with two levels of EP lubricants were compared with a fluid that did not contain EP lubricants. The fluid with the highest EP level gives six to nine times higher G-ratios than the non-EP containing fluid. The combination of the sol-gel wheel with the highest-EP-level fluid results in a 56-fold increase in G-ratio over that of the conventional aluminum oxide wheel with the non-EP-containing fluid. The grinding efficiency (E) remains constant as Q' increases with the combination of sol-gel grinding wheels with both of the EP-containing grinding fluids. All other combinations of wheels and fluids demonstrated the expected trend of decreasing E as Q' increased. Based on these data, G-ratio, specific energy (U) and specific material removal rate (Q'), the total productivity improvement of sol-gel wheels with the highest-level EP-containing fluid is 130 times better than that of the conventional aluminum oxide wheel and grinding fluid with no EP lubricant. Using the same combination of wheel and high-EP-containing fluid, the surface finish of the ground parts is better than that obtained with other wheel/fluid combinations. As Q' increases, the rate of surface roughness increases less with the sol-gel wheel and high-EP-containing fluids than with other wheel/fluid combinations.

Introduction

Grinding wheels are categorized by the type of abrasive they contain. The grinding process utilizes these abrasive particles as cutting edges in random contact with the material to be worked. The two major categories of grinding wheels are conventional and super-abrasive. The conventional grinding wheels are low performance and contain lower-cost abrasives such as aluminum oxide (Al_2O_3) and silicon carbide (SiC). The super-abrasive wheels are higher performance and contain high-cost abrasives consisting of diamond or cubic boron nitride (CBN). In many applications, manufacturing industries cannot achieve their productivity goals with conventional grinding wheels. The use of a super-abrasive grinding wheel is prohibitively expensive and complex for many machine shops. Therefore, a limited number of manufacturing companies are using super-abrasive wheels in their grinding operations.

Fluids fall into two major categories: straight cutting oils and water-dilutable fluids [1-4]. The straight cutting oils provide good grinding performance. However, they are being phased out by many major manufacturers due to fire hazard concerns, process restrictions, environmental concerns, and health considerations. The water-dilutable grinding fluids are usually subdivided into three categories: Synthetics, Semi-Synthetics, and Soluble Oils. Based on the chemistry of the concentrates, synthetic fluids typically contain water and water soluble components. Semi-synthetic concentrates contain both water soluble and oil soluble components, while soluble oil concentrates contain mostly oil and oil soluble components. Soluble oils and semi-synthetics may contain extreme pressure lubricants (EP) [5-7].

For decades, manufacturing industries have been looking for efficient ways to reduce grinding costs and improve productivity and part quality. C. A. Smits [8] summarized the effects of metalworking fluids on productivity, tool life, energy consumption, and part quality of grinding systems. R.P. Lindsay [9] found that the use of a heavy-duty soluble oil grinding fluid reduced grinding specific power by about 1.5 times compared to a synthetic grinding fluid. H.K. Tonshoff et al. [10] reported that, with a conventional alumina grinding wheel, a straight oil provided 2 to 6 times higher G-ratio than an emulsion grinding fluid. S. C. Yoon and M. Krueger [11-12] recently discovered that a 50-percent sol-gel wheel with QUANTALUBE™ 270* (a water-dilutable soluble oil fluid) generated 4 to 6.5 times higher grinding ratios compared to a conventional grinding wheel, 29A, with a conventional semi-synthetic fluid, CIMSTAR 40 on 4150 steel. These results encouraged us to continue evaluating other combinations of wheels and fluids for further improvement on grinding performance.

Materials and Experimental Methods

This study compares the performance of two different Milacron Inc. grinding wheels and three different Milacron grinding fluids under various grinding conditions. The two Milacron wheels are a conventional aluminum oxide wheel with Milacron designation 29A, and a 30%-sol-gel wheel with Milacron designation 3MSB™ *. The three Milacron grinding fluids are CIMSTAR™ 40*, which contains no EP lubricants; QUANTALUBE 270, which contains a reasonably high level of EP lubricant; and QUANTALUBE 275, which contains the highest available level of EP lubricants. The grinding performance was evaluated in terms of grinding ratio, grinding energy, grinding efficiency and surface roughness of the ground parts over a wide range of specific material removal rates. The 3MSB grinding wheels [13-14] and the QUANTALUBE metalworking fluids are patented by Milacron Inc.

Grinding Machine

The Weldon Model AGN5 CNC cylindrical grinder shown in Figure 1 is located at the Oak Ridge National Laboratory's High Temperature Materials Lab (HTML). Table 1 shows the major capabilities of the grinder. This grinder was used to perform all grinding tests discussed in this report. Although the grinder has both an OD spindle and an auxiliary spindle for ID grinding, only the OD spindle was used, and all grinding was done in a plunge mode. The grinder is fully instrumented to facilitate data collection

Figure 1. The Weldon Model AGN5 CNC cylindrical grinder.

* 3MSB, QUANTALUBE, and CIMSTAR are trademarks of Milacron Inc.

Table 1. Specifications for the Weldon AGN5 cylindrical grinder.

Machine type	Weldon AGN5 cylindrical grinder
Grinding spindle motor	Variable speed AC servo motor 11.25 kW (15 HP)
Grinding spindle bearing type	Angular contact bearing with silicon nitride balls
Workhead speed	100 RPM
Workhead rotational direction	Opposite direction from grinding wheel
Radial plunge speeds	0.03638, 0.05457, 0.07276, 0.09095, and 0.10914 in/min
Width of plunge grinding	(0.5 inch)

and analysis. During each experimental run, spindle power consumption was measured using an inductive sensor and National Instruments LabView® software. (LabView is a commercially available product of the National Instruments Corporation.)

Grinding Wheels

Two different types of Milacron grinding wheels were used for these grinding studies. The specification of the first wheel is 29A601-J6-VRW, containing 40% brown fused alumina and 60% white fused alumina abrasive. The specification of the second wheel is 3MSB601-J6-VSA, containing 70% white fused alumina and 30% CUBITRON™* 321 abrasives. CUBITRON 321 is a sol-gel alumina abrasive manufactured by the 3M Company. CUBITRON 321 contains sub-micron crystals that have micro-fracturing capability [15]. To further increase the fracture toughness of this sol-gel abrasive, CUBITRON 321 contains a secondary phase. This phase is in the form of platelets or particles that can be successfully grown during manufacturing of the sol-gel ceramic matrix without significant loss in density or microhardness [16].

These wheels contained 89.5% abrasive and 10.5% vitrified bond by weight. Both wheels contained 48.46% abrasives, 9.36% bond and 42.18% porosity by volume. The 3MSB wheels were manufactured by a special manufacturing technique described in U.S. Patent No. 5037452[14]. Wheel densities are 2.15 g/cc for both the 29A wheel and the 3MSB wheel. Elastic moduli are also similar, 6.93 and 6.86 x 10^6 psi for the 29A wheel and the 3MSB wheel, respectively.

Initial dimensions for all wheels used in this experiment were 16-inches outer diameter, 5.0-inch bore, and 1.0-inch thickness. As the tests progressed, the outer diameter of the wheels decreased due to wear and truing. A constant surface speed was maintained by adjusting RPM slightly to compensate for changes in wheel diameter.

* CUBITRON is a trademark of the 3M Company, and LabView is a registered trademark of National Instruments..

Grinding Fluids

Both QUANTALUBE 270 and 275 are EP-containing, water-dilutable, metalworking fluids while CIMSTAR 40 is a non-EP-containing semi-synthetic fluid. QUANTALUBE 275 contains more sulfurized EP than QUANTALUBE 270, which is formulated with three different sulfurized EP's. All fluids were evaluated as a 5% solution.

Workpiece

All workpiece specimens were 52100 tool steel, with a nominal hardness of 58-60 R_c. The workpiece dimensions were 4" outside diameter, 1.25" inside diameter, and 0.5" in thickness.

Truing and Dressing Process

Truing is defined as the process of shaping the grinding wheel while it is mounted on the grinding spindle in order to remove out-of-roundness and to impart the desired profile to the surface of the wheel. Dressing, which is sometimes performed after truing, is the process of conditioning the surface of the wheel to expose fresh abrasive particles. The grinding wheel was trued before each experimental run. Approximately 0.060 inch of wheel material was removed by truing before each experimental run during early tests. In subsequent tests that used more aggressive in-feed rates, 0.120 inch of material was removed from the wheel between the tests. A truing tool similar to the one shown in Figure 2 was used for all truing operations. Truing parameters are shown in Table 2. Figure 3 shows the wheel and the multi-cut truing tool mounted in the grinder prior to truing the wheel.

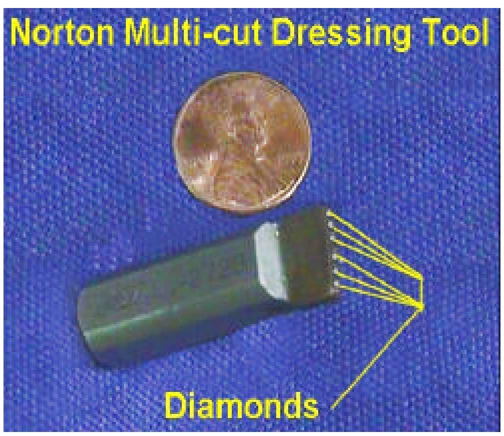

Figure 2. A Norton LL2728 Multi-Cut truing tool was used for all truing operations.

Table 2. Truing parameters used in all tests.

Truing device	Multi-cut LL2728
Truing device manufacturer	Norton
Speed of grinding wheel during truing	6000 surface feet per minute (automatically adjusted for changing wheel diameters)
Radial in-feed during truing	0.002 inch per pass, 0.001 inch per pass (during last 0.005 inch)
Truing traverse speed	6 inch/min

Figure 3. Grinding wheel and Multi-cut truing/dressing tool prior to truing the wheel.

Grinding Procedure

All grinding was performed at a surface speed of 6,000 surface feet per minute, which is approximately 1430 RPM for a 16-inch diameter wheel. Each test specimen was mounted between centers as shown in Figure 4. Nominal work-head (specimen) speed was 100 RPM, and the work-head was rotated in the opposite direction from that of the grinding wheel. Work-head speed was automatically varied to maintain a constant surface speed for the workpiece during grinding. Prior to each test, the workpiece was ground to ensure that its outer diameter was running true, and the grinding wheel was then trued. The outer diameters of both the workpiece and the grinding wheel were measured. The diameter of the workpiece was then reduced by approximately 1.0 inch during the grinding test. No dwell (spark out) time was provided at the end of the plunge cut. The final diameter of the workpiece was measured and recorded. In-feed (radial plunge) rates were varied as shown in Table 1 to achieve specific material removal rates (Q') of 0.4, 0.6, 0.8, 1.0, and 1.2 in^3/ min per inch of wheel width.

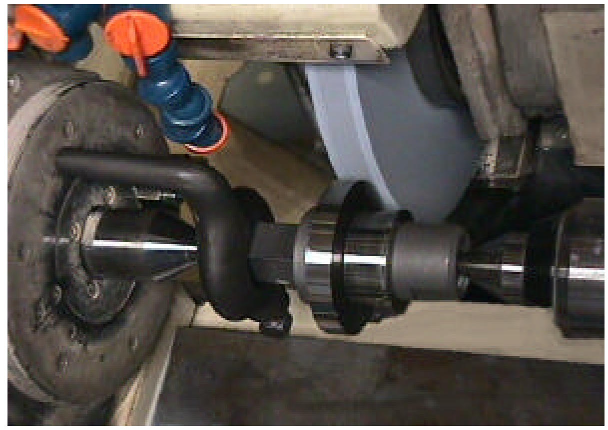

Figure 4. The Weldon grinder shown with 52100 steel test part mounted between centers.

Grinding Power Measurement

The power required to drive the grinding spindle was measured for each grinding test using data collection software written in LabView. A typical plot of spindle horsepower versus time is shown in Figure 5.

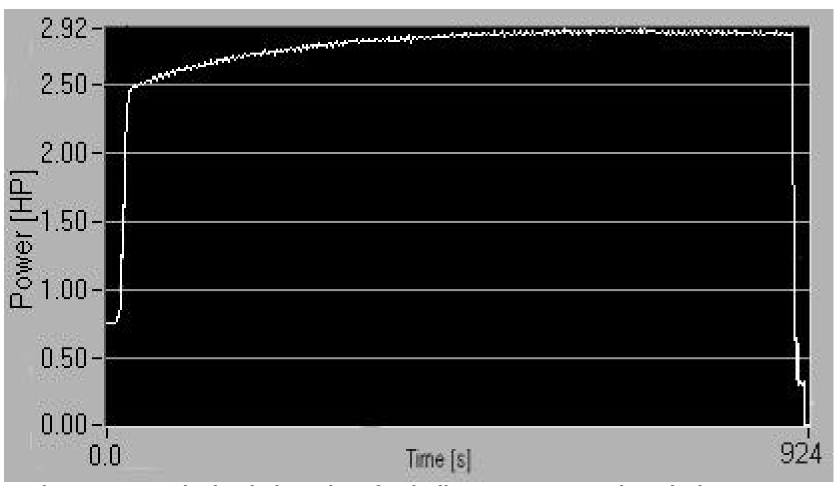

Figure 5. A typical Labview plot of spindle power versus time during a grinding experiment.

Wheel Wear Measurement

After each grinding test, a plastic wear specimen was ground to produce a mirror image of the wheel surface, as shown in Figure 6. The wear specimen was then measured on the Electronic Measuring Devices *Legend* coordinate measuring machine shown in Figures 7a and 7b.

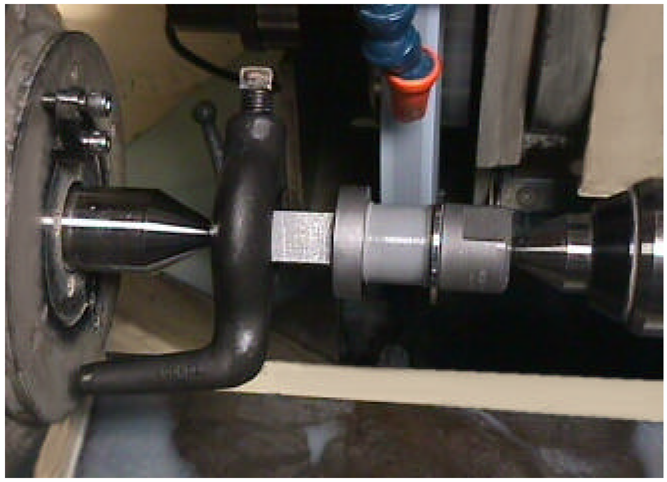

Figure 6. Preparing to grind the wear specimen, mounted between centers, on the Weldon grinder.

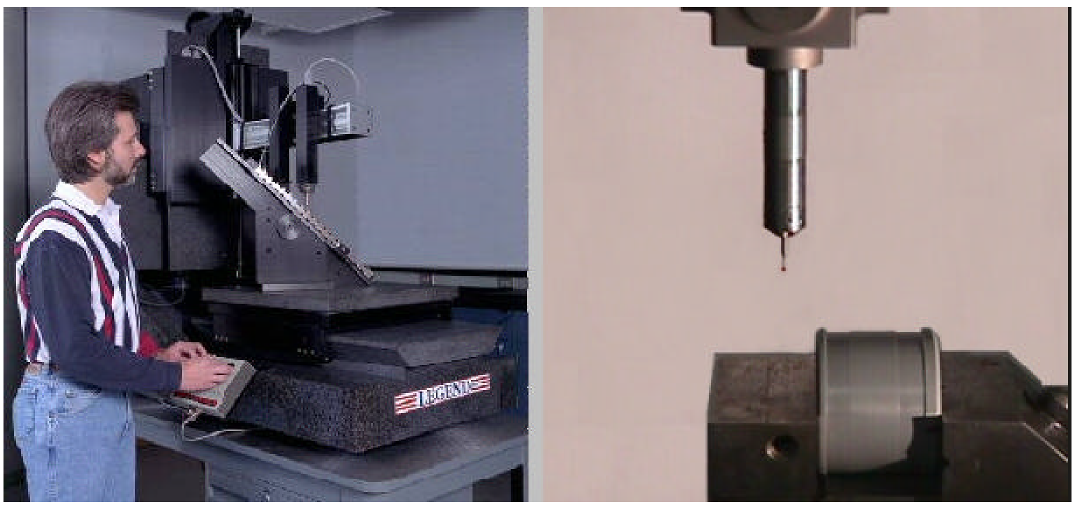

Figure 7. (a) The Electronic Measuring Devices (EMD) Legend coordinate measuring machine (CMM). (b) The wear specimen mounted on the CMM in preparation for measurement.

Surface Finish Measurement

The surface roughness of each test specimen was measured using the Taylor-Hobson Talysurf Model 120 surface profiling instrument shown in Figure 8.

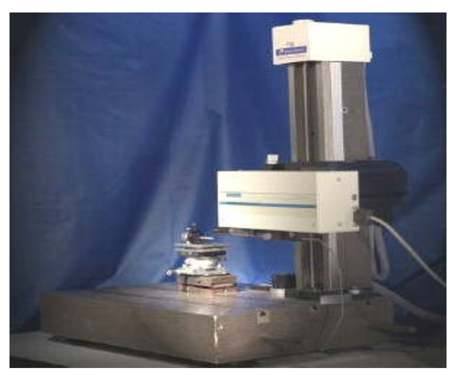

Figure 8. The Taylor Hobson Talysurf Model 120, Series 1 surface profiling instrument was used to measure surface finish of each workpiece.

Results and Discussion

The grinding results are summarized in terms of grinding ratio, specific energy, grinding efficiency, and surface roughness.

Grinding Ratio, G

Wheel life in grinding is expressed as a grinding ratio, G, defined as the volume of material removed per unit volume of grinding wheel wear. G-ratio is an important parameter because it is directly related to wheel cost for most operations. Wheels with a high G-ratio last longer and produce more parts between dressing cycles than those with lower G-ratios.

Figures 9a and 9b present the grinding ratio (G) data for the 29A wheel and 3MSB wheel using three different grinding fluids (5% solution): CIMSTAR 40, QUANTALUBE 270, and QUANTALUBE 275. The tests were run at different specific material removal rates. The specific material removal rate, Q', is defined as the volume of material removed per unit of time per unit of effective wheel width. Its units are in cubic inches per minute per inch of effective wheel width (in.^{3}/ min./ in.). The productivity of a grinding process is expressed by this specific material removal rate. A larger Q' means material is being removed faster.

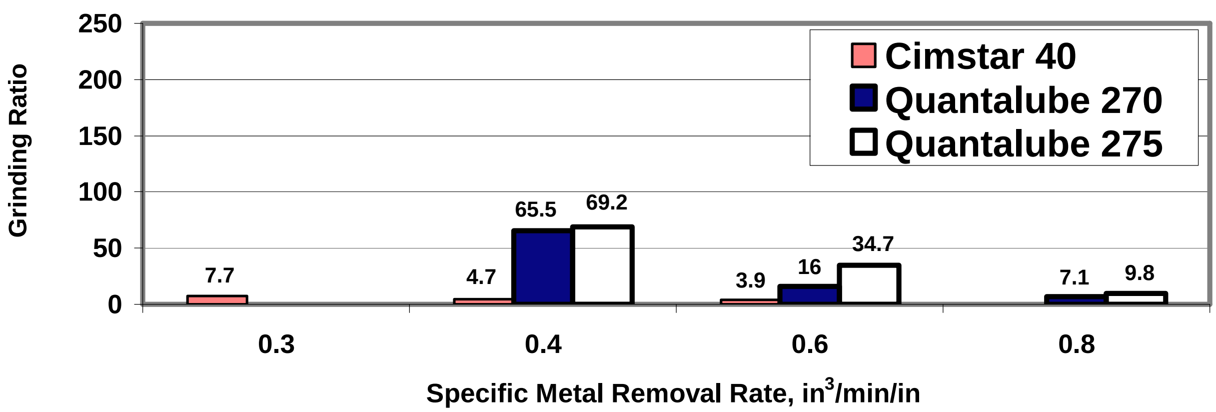

Figure 9a. Grinding Ratio for Cimstar 40, Quantalube 270, and Quantalube 275 with 29A601-J6-VRW Wheel

Based on the data, the G-ratio decreases as the Q' (material removal rate) increases, as expected. Among all the combinations of grinding wheels and metalworking fluids, the 3MSB with QUANTALUBE 275 or 3 MSB with QUANTALUBE 270 greatly outperformed all other combinations. QUANTALUBE 275 provided the highest G-ratios for all the Q' tested (0.4 to 1.2). The 3MSB with QUANTALUBE 270, the second best combination, typically had G-ratios 75 units less than the QUANTALUBE 275 with 3MSB. The worst combination was 29A with CIMSTAR 40, which simulates what is used in many traditional grinding applications. The 3MSB grinding wheels provided significant improvement in grinding performance compared to the 29A grinding wheels. QUANTALUBE 275 outperformed QUANTALUBE 270, which greatly outperformed CIMSTAR 40. Wheel breakdown during grinding was significantly greater for the 29A wheels compared to the 3MSB wheels at higher Q'. The breakdown of the grinding wheels is due to high forces. If the grinder is run at high Q', causing high forces, damage will occur to either the grinder or the grinding wheel, therefore, the grinding test data for CIMSTAR 40 is not available at Q' > 0.8.

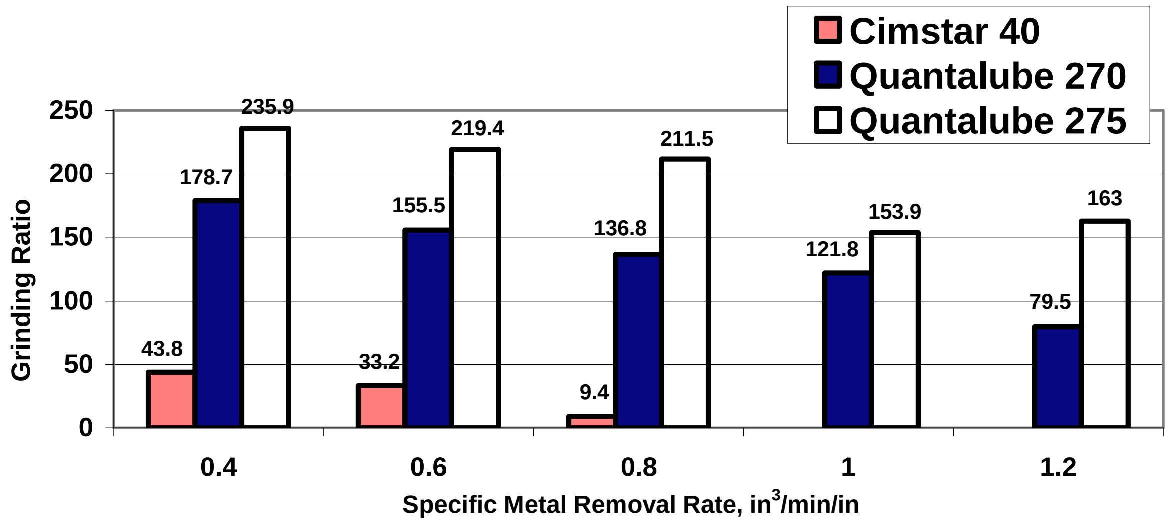

Figure 9b. Grinding Ratio for Cimstar 40, Quantalube 270 and Quantalube 275 with 3MSB601-J6-VSA wheel.

At a Q' of 0.6, the grinding ratios of the 29A wheel were 3.9, 16, and 34.7 for CIMSTAR 40, QUANTALUBE 270, and QUANTALUBE 275, respectively. Replacing the 29A grinding wheel with 3MSB while maintaining all other conditions the same, resulted in grinding ratios of 33.2, 155.5, and 219.4 respectively. This means that the 3MSB wheel generates 8 to 10 times (43.8/4.7=9.3) higher G-ratio than the 29A wheel, and QUANTALUBE 275 results in 6 to 9 times higher G-ratio than CIMSTAR 40. In addition, the combination of the 3MSB wheel with QUANTALUBE 275 provides 56 times (219.4/3.9=56.3) higher G-ratio than that of the 29A wheel with CIMSTAR 40.

At a Q' of 1.2 (double the material remove rate mentioned above) the grinding ratios of 3MSB wheels with QUANTALUBE 270 and 275 were 79.4 and 163 respectively. In other words, one can grind twice as fast with wheels lasting 20 times (79.5/3.9=20.4) longer with QUANTALUBE 270 or 42 times (163/3.9=41.8) longer with QUANTALUBE 275 than the combination of 29A wheel with CIMSTAR 40.

The sulfurized EPs found in QUANTALUBE 270 and QUANTALUBE 275 react with the metal surface forming a low shear film. This thin layer of reacted film provides additional lubrication for the grinding process, significantly reducing the coefficient of friction at the interface between the grinding wheel and the workpiece [17-20]. The low coefficient of friction reduces forces resulting in less wheel breakdown and a higher G-ratio.

The mechanism that we have theorized for this grinding improvement is as follows:
When grinding with fused alumina (29A) and CIMSTAR 40, the abrasive becomes dull quickly. As it becomes dull, the force between the wheel and the workpiece builds up until the bond can no longer hold the grain, which breaks free from the grinding wheel (wheel breakdown). The use of EP-containing fluids (QUANTALUBE 270 and 275) slows the dulling process of the abrasives by reducing the friction between the abrasives and workpiece, resulting in longer wheel life and higher G-ratios.

The G-ratio value is affected by both the manner in which the grain fractures and the structure of the grinding wheel. When grinding with CUBITRON 321 (3MSB), the abrasive also becomes dull. However, the CUBITRON 321 grain fractures in groups of sub-micron crystals before the forces build to a level that would cause the grain to dislodge. As discussed above, EP-containing fluids such as QUANTALUBE 270 and QUANTALUBE 275 reduce the friction between the abrasive and the metal part, resulting in significantly less wheel wear and more efficient fracturing of the CUBITRON abrasive.

Specific Energy, U

The energy consumption in grinding is described by the specific energy (U). U is defined as the amount of energy (horsepower times grinding time) required to remove one unit volume of material. Figures 10a and 10b show the specific energy data of the 29A wheel and 3MSB wheel at different Q', (0.3 to 1.2). In

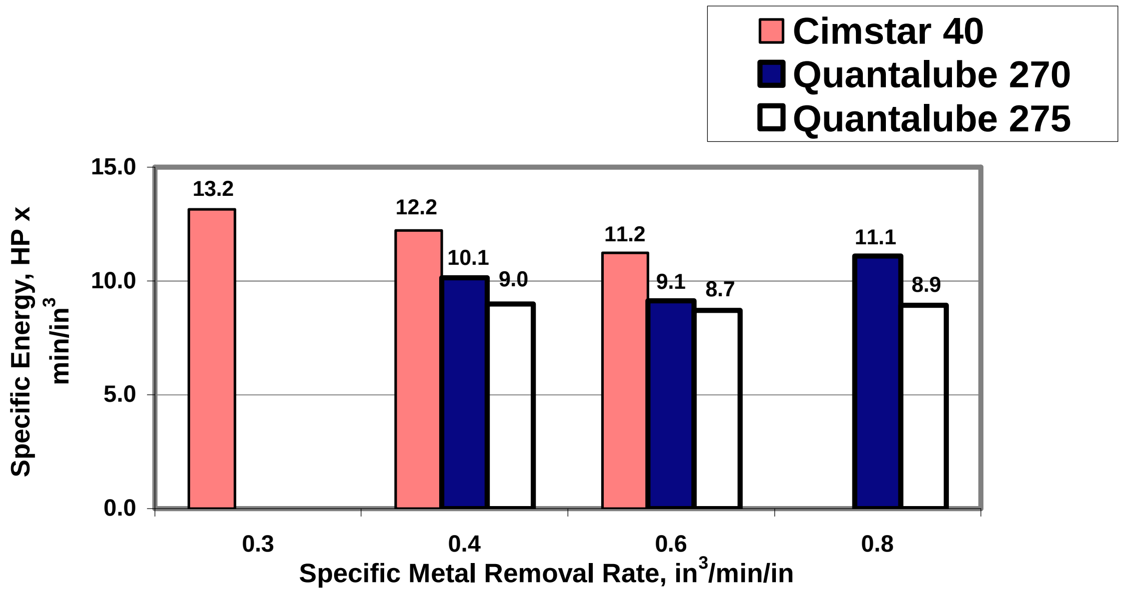

Figure 10a. Specific Energy for Cimstar 40, Quantalube 270, and Quantalube 275 with 29A601-J6-VRW Wheel.

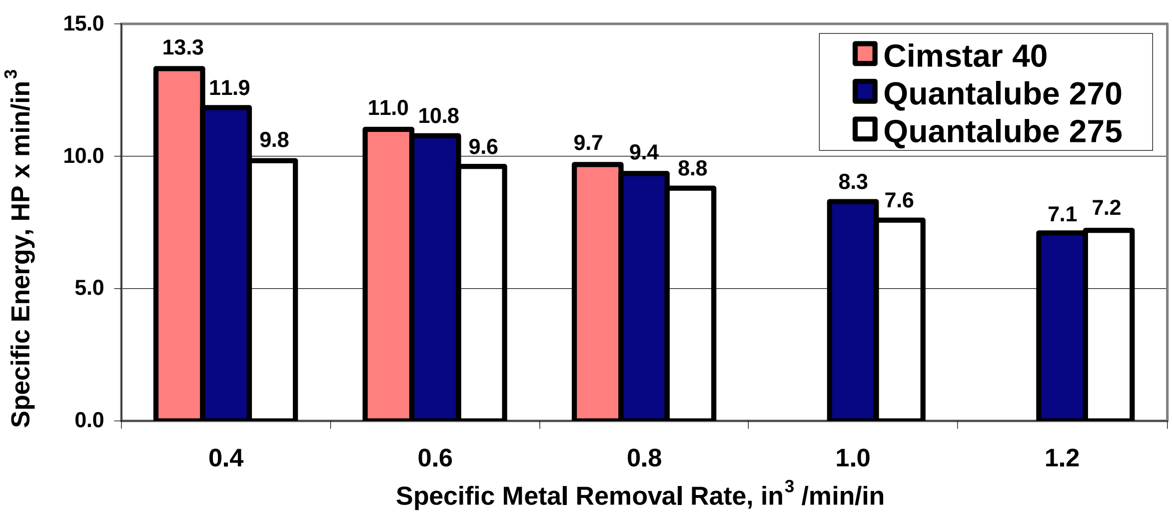

Figure 10b. Specific Energy for Cimstar 40, Quantalube 270 and Quantalube 275 with 3MSB601-J6-VSA wheel.

general the U value decreases as the Q' increases for both the 29A and the 3MSB wheels. Generally, at equivalent grinding conditions, CIMSTAR 40 uses more energy to grind than QUANTALUBE 270, which uses more than QUANTALUBE 275. In other words, the specific energy increased as the concentration of EP decreased in the metalworking fluids.

At a Q' of 0.6, the specific energies (U) for the 29A wheels were 11.22, 9.13, and 8.71 for CIMSTAR 40, QUANTALUBE 270, and QUANTALUBE 275, respectively. At the same Q' (0.6), the specific energies of 3MSB wheels were 11.01, 10.78, and 9.62 for CIMSTAR 40, QUANTALUBE 270, and QUANTALUBE 275, respectively. These differences between wheels are insignificant because wheel breakdown produced large variations in horsepower.

Grinding Efficiency, E

In order to determine the effective grinding performance, we have to consider both wheel life (grinding ratio) and energy consumption (specific energy). The grinding efficiency, E, is defined as the grinding ratio (G) divided by specific energy (U). Figures 11a and 11b display the grinding efficiency data for the combinations of grinding wheels and grinding fluids at different specific material removal rates. The grinding efficiency is closely related to grinding productivity and energy consumption in the grinding process. A higher grinding efficiency results in higher productivity and lower energy consumption.

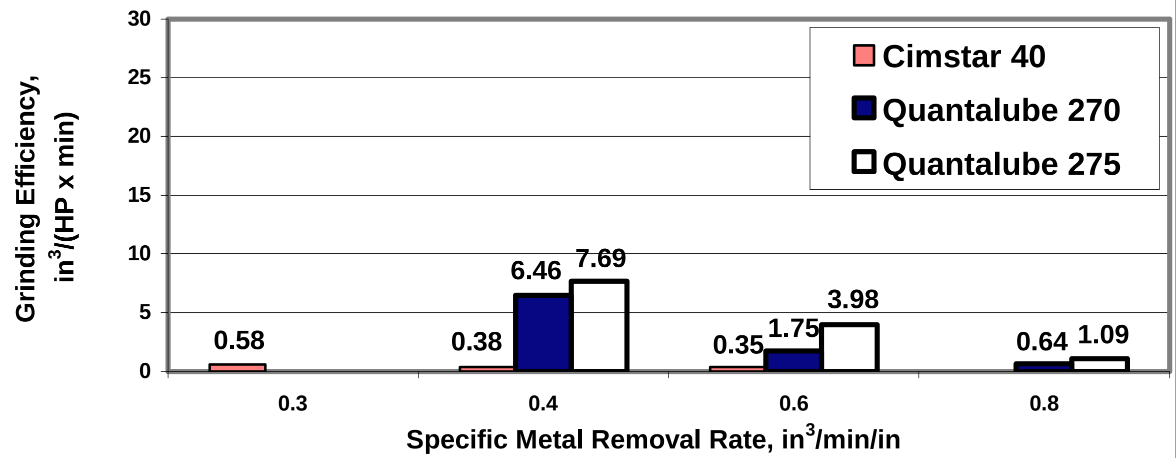

Figure 11a. Grinding Efficiency using Cimstar 40, Quantalube 270, and Quantalube 275 with 29A601-J6-VRW Wheel.

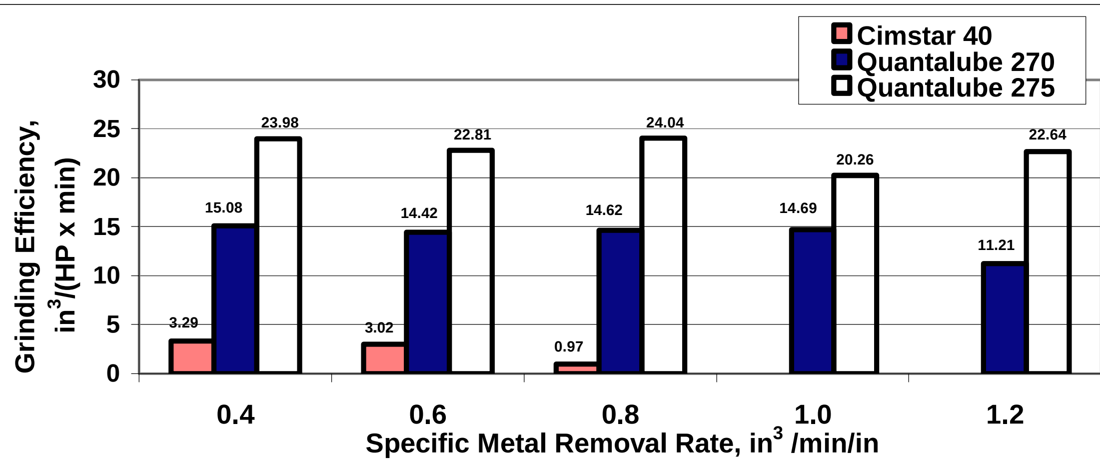

Figure 11b. Grinding Efficiency using Cimstar 40, Quantalube 270 and Quantalube 275 with 3MSB601-J6-VSA wheel.

Based on these data, the combination of 3MSB wheel and QUANTALUBE 275 metalworking fluid demonstrated the highest grinding efficiencies for all Q's (0.4 to 1.2). In addition, E remained nearly constant, averaging 22.75, as Q' increased. We would expect E to decrease as Q' increased. The second best combination was the 3MSB wheel and the QUANTALUBE 270 fluid. Grinding Efficiency (E) also remained constant, averaging 14.7, from a Q' of 0.4 to 1.0. However, it dropped to 11.2 (24%) when Q' increased to 1.2. Both combinations of 3MSB + QUANTALUBE 275 and 3MSB + QUANTALUBE 270 had significantly higher grinding efficiency than the remaining four combinations. The worst combination was the 29A wheel and the CIMSTAR 40 fluid. For the other three combinations, E decreased significantly as Q' increased.

At a Q' of 0.6 the grinding efficiencies for the 29A wheels were 0.35, 1.75, and 3.98 using CIMSTAR 40, QUANTALUBE 270, and QUANTALUBE 275, respectively. At the same grinding conditions, the grinding efficiencies for the 3MSB wheels were 3.02, 14.42, and 22.81, respectively. Therefore, by simply replacing the grinding wheel the grinding efficiency was improved by a factor of five to eight. Furthermore, at Q' = 1.2, the grinding efficiencies for the 3MSB wheels were 11.21 and 22.64 for QUANTALUBE 270 and 275, respectively. Comparing the grinding efficiency of 3MSB with QUANTALUBE 275 at Q'=1.2 to that of a more traditional combination, the 29A grinding wheel using CIMSTAR 40, at Q'=0.6, it is easy to see that 3MSB with QUANTALUBE 275 could improve grinding efficiency by 65 (22.64/0.35=64.69) times. In other words, by using the 3MSB wheel with QUANTALUBE 275, one can improve productivity by a factor of 65 when compared to a traditional aluminum oxide grinding wheel using a common non-EP-containing grinding fluid. However, since Q' is two times higher (1.2/ 0.6 =2), the total improvement of the 3MSB wheel with QUANTALUBE 275 would be 130 times better than the 29A wheel with CIMSTAR 40.

Surface Roughness, R_a

The quality of a part is often measured as surface roughness (R_a), which is the arithmetic mean of departures of roughness profile from the mean line. The lower the surface roughness, the higher the quality of the ground part. Figures 12a and 12b present the surface roughness data of the workpieces ground with different combinations of wheels (29A and 3MSB) and fluids (CIMSTAR 40, QUANTALUBE 270, and QUANTALUBE 275).

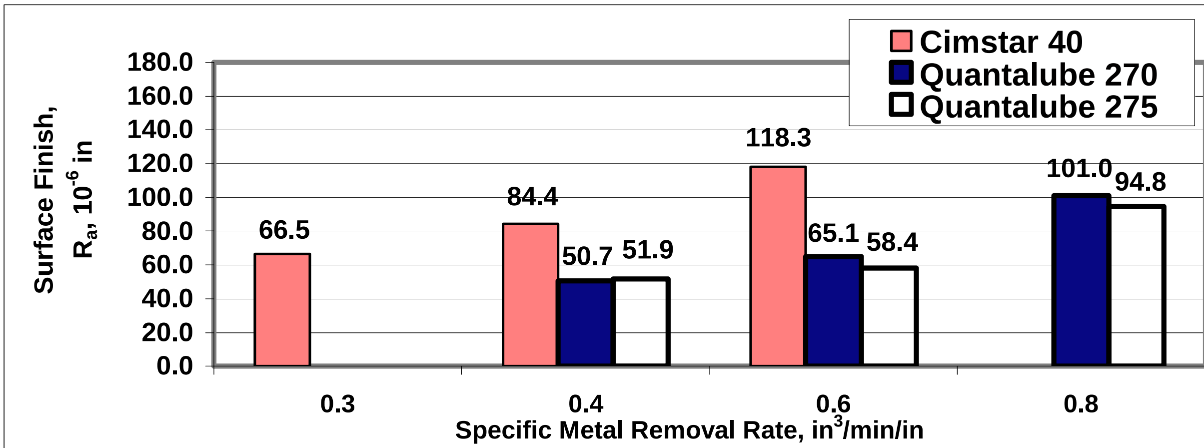

Figure 12a. Surface Finish using Cimstar 40, Quantalube 270, and Quantalube 275 with 29A601-J6-VRW Wheel.

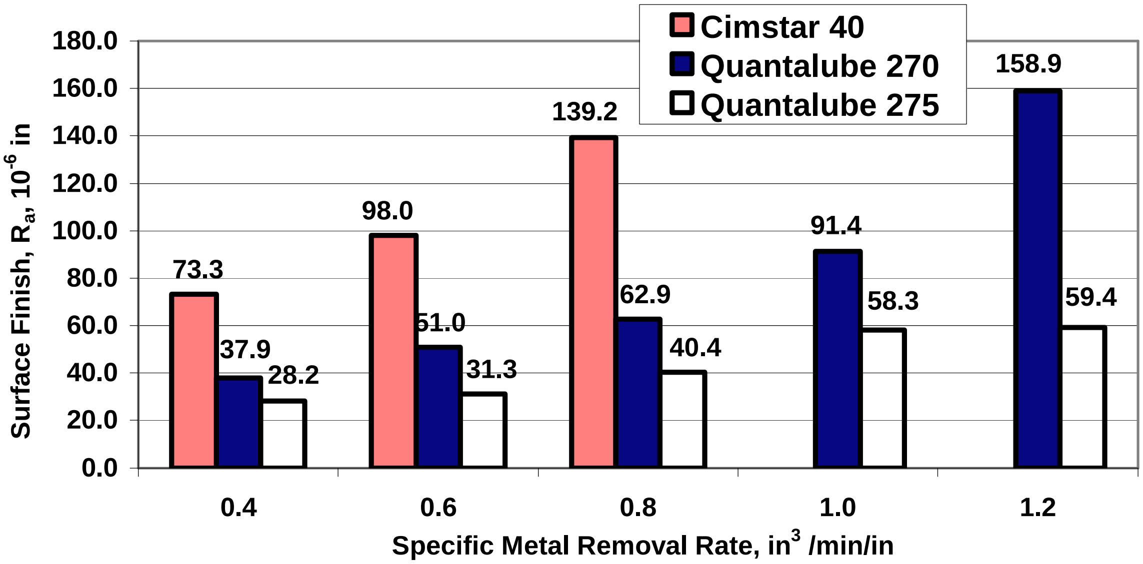

Figure 12b. Surface Finish using Cimstar 40, Quantalube 270 and Quantalube 275 with 3MSB601-J6-VSA wheel.

According to these surface roughness data at each Q', the highest R_a was achieved with CIMSTAR 40 and the lowest R_a was achieved with QUANTALUBE 275 metalworking fluid. This indicates that the surface roughness of the parts was significantly improved by using EP-containing fluids (QUANTALUBE 270 and QUANTALUBE 275). For example, in the Q' range from 0.4 to 0.6, the surface roughness of the parts ground by 29A with CIMSTAR 40 is about 40% higher than with QUANTALUBE 270 or QUANTALUBE 275.

The type of grinding wheel also affects the surface roughness. At a Q' of 0.6 using a 29A grinding wheel, the R_a values were 118.25, 65.05, and 58.35 for CIMSTAR 40, QUANTALUBE 270, and QUANTALUBE 275, respectively. With the 3MSB wheel, the R_a values were 98, 51, and 31.3 for CIMSTAR 40, QUANTALUBE 270, and QUANTALUBE 275, respectively. These data show that the 3MSB wheel itself could improve the surface roughness over the 29A wheel by 17% with CIMSTAR 40, 22% with QUANTALUBE 270, and 46% with QUANTALUBE 275.

It has been found that the surface roughness of the ground part increased as Q' increased. In the case of CIMSTAR 40 with 29A or 3MSB wheels, the surface roughness increased by almost 100% when Q' was doubled (from 0.3 to 0.6 for 29A and from 0.4 to 0.8 for 3MSB). However, the surface roughness only increased by 43% as Q' increased from 0.4 to 0.8 when the 3MSB wheel was lubricated with QUANTALUBE 275. Comparing the surface roughness data for QUANTALUBE 270 to that for QUANTALUBE 275, as shown in Figure 12b, it can be seen that the surface roughness increased by 319% for QUANTALUBE 270 but only by 111% for QUANTALUBE 275 as Q' increased from 0.4 to 1.2. This indicates that more EP lubricant is needed in the grinding fluid when the grinder is operated under severe grinding conditions.

These surface roughness data demonstrate a significant quality improvement of the workpiece for the combination of the 3MSB wheel with QUANTALUBE 275. It is believed that this phenomenon is closely related to both the fracturing mechanism and the rate of micro-fracturing of the abrasive grain in the 3MSB wheel, as well as the reduced friction between the workpiece and abrasive grain due to the EP lubricants found in QUANTALUBE 275.

Conclusions

The effects of grinding wheels, grinding fluids, and their different combinations on the grinding ratio, specific energy, grinding efficiency, and surface roughness have been investigated over a wide range of specific material removal rates. The following conclusions, which have been verified only for ground 52100 steel parts, were obtained.

1. The maximum Q' achieved was 0.6 for the 29A wheels with CIMSTAR 40. However, Q' was higher than 1.2 (more than double) for the 3MSB wheels with Q-270 or Q275.

2. For a given wheel and fluid combination, the G-ratio decreases with increasing material removal rate. The 3MSB grinding wheel generates eight to ten times higher G-ratio than the 29A wheel. EP containing QUANTALUBE 275 grinding fluid gives six to nine times higher G-ratio than non-EP-containing CIMSTAR 40. The combination of 3MSB with QUANTALUBE 275 resulted in a G-ratio 56 times greater than that of a standard metalworking fluid and grinding wheel, CIMSTAR 40 with 29A .

3. Typically, the specific energy (U) decreases with the increase in material removal rate (Q'). Generally, CIMSTAR 40 uses more energy to grind than QUANTALUBE 270, which uses more than QUANTALUBE 275.

4. With 3MSB grinding wheels and EP-containing fluids such as QUANTALUBE 270 and QUANTALUBE 275, the grinding efficiency remained constant. For all other combinations of wheels and fluids, the E decreased as Q' increased.

5. The total productivity improvement of 3MSB wheels with QUANTALUBE 275 is 130 times better than the 29A wheels with CIMSTAR 40, based on improvements in G-ratio, specific energy (U), and specific material removal rate (Q').

6. The surface roughness of the ground parts increased as the material removal rate increased for all wheels and fluids combinations. However, among all combinations evaluated in this study, the combination of 3MSB with QUANTALUBE 275 generated the least increase in surface roughness, as the material removal rate increased.

Acknowledgements

Portions of this research were 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 UT-Battelle, LLC, for the U.S. Department of Energy under contract number DE-AC05-00OR22725. The authors would like to acknowledge significant contributions to this effort by the following people: Ralph Kelly, Roger Gary, Charlie Yang, Robert McFarland, and Jerry Byers at Milacron Inc.; and Larry Walker at Oak Ridge National Laboratory.

References

[1] J. J. O'Connor, J. Boyd, and E. A. Avallone, *Standard Handbook of Lubrication Engineering*, McGraw-Hill book Company, New York, 1968, Chapter 23.

[2] J. A. Schey, *Tribology in Metalworking*, American Society For Metals, 1983, Chapter 11.

[3] H.W. Wagner, *Mech. Eng.,* 73, 1951, 128-132.

[4] L. P. Tarasov, *Tool Manuf. Eng.,* 46(7), 1961, 67-73.

[5] J. C. Childers, “The Chemistry of Metalworking Fluids”, *Metalworking Fluids,* Marcel Dekker, New York, 1994, 165-189.

[6] G. Foltz and H. Noble, “Metal Removal: Fluid Selection and Application Guide”, *Tribology Data Handbook,* CRC Press, New York, 1997, 831-839.

[7] E.S. Nachtman and S. Kalpakjian, *Lubricants and Lubrication in Metalworking Operations*, Marcel Dekker, New York, 1985.

[8] C.A. Smits, “Metalworking Fluids in Grinding System”, *Metalworking Fluids,* Marcel Dekker, New York, 1994, 99-134.

[9] R.P. Lindsay, Paper No. MR74-120, SME, Dearborn, 1974.

[10] H.K. Tonshoff, P.G. Althaus, and H.H. Nolke, *Metalworking lubrication,* ASME, New York, 1980, 217-223.

[11] S.C.Yoon and M. Krueger, “Optimizing Grinding Performance by the Use of Sol-Gel Alumina Abrasive Wheels and a New Type of Aqueous Metalworking Fluid”, Machining Science and Technology, 3(2), 287-294 (1999), Marcel Dekker, New York.

[12] S. C. Yoon and M. Krueger, “A Killer Combination for Ideal Grinding Conditions”, *American Machinist,* Penton Media, Inc. Cleveland, November 1998.

[13] W. P. Wood and S. C. Yoon, “ High Density Sol-Gel Alumina- Based Abrasive Vitreous Bonded Grinding Wheel” , U. S. Patent No. 5282875, Feb. 1, 1994.

[14] R. A. Gary and S. C. Yoon, “ Method of Making Vitreous Bonded Grinding Wheels and Grinding Wheels Obtained by the Method”, U. S. Patent No. 5037452, Aug. 6, 1991.

[15] M. G. Schwabel and P. E. Kendall, “ Alumina Abrasive Grains Produced by Sol-Gel Technology”, Am. Ceram. Soc. Bull. 66[10]: 1596-98; 1991.

[16] D. D. Erickson and W. P. Wood, “ In-Situ Magnetoplumbite Growth in Sol-Gel Derived Alimina Matrices”, Ceram. Trans. Vol. 46, pp. 463-74, 1994.

[17] E.S. Forbes, *Tribology,* 3, 1970, 145-152.

[18] E.S. Forbes and A.J.D. Reid, *ASLE Trans.*, 16, 1973, 50-60.

[19] I.M. Hutchings, *Tribology: Friction and Wear of Engineering Materials,* CRC Press, Boca Raton, FL. USA, 1992, 70-73.

[20] P. Kapsa and J.M. Martin, *Trib. Int.,* 15, 1982, 37-42.