Development of Novel CBN Grade for Electroplated Finish Grinding of Hardened Steel Gears

The unique requirements of an electroplatable superabrasive CBN grit used in profile grinding of hardened steel gears, as well as the attributes and grinding behavior of a new CBN developed specifically for this application, are discussed.

By Uppili Sridharan, Shuang Ji, Sridhar Kompella, and James Fiecoat
THE GRINDING PROCESSES USED IN FINISH GRINDING OF HARDENED GEARS CAN BE CLASSIFIED AS GENERATING GRINDING AND PROFILE GRINDING, DEPENDING ON HOW THE PROFILES OF GEAR TEETH ARE FINISHED. THE GRINDING PROCESS CAN BE CONTINUOUS, WHERE THE GEAR PROFILE IS ACHIEVED PROGRESSIVELY BY GRINDING WITH A SPLINED WHEEL, OR DISCONTINUOUS PROFILE GRINDING, WHERE A SPECIFIC PROFILE IS GROUND ONE GEAR TOOTH AT A TIME.

CONTINUOUS GENERATING GRINDING IS TYPICALLY ADOPTED WHEN GRINDING SMALL BATCHES WITH VARYING GEAR PROFILES AND HENCE USES DRESSABLE CONVENTIONAL ALUMINUM OXIDE WHEELS INTO WHICH PROFILES CAN BE EASILY DRESSED USING A DIAMOND DRESSING TOOL. IN CERTAIN SPECIAL CASES WHERE MAINTAINING GEAR SURFACE INTEGRITY IS IMPORTANT, VITRIFIED BONDED CBN WHEELS MAY BE PREFERRED OVER CONVENTIONAL VITRIFIED WHEELS [1].

Discontinuous profile grinding is generally used in a high-volume repetitive process and typically uses an electroplated superabrasive CBN wheel. Electroplated CBN wheels contain a single layer of abrasive embedded in a nickel matrix and have the negative profile of the gear tooth ground with abrasive protrusion tolerance typically less than 5 µm. This is essential to achieve accurate profile on each gear tooth due to the single-pass nature of the process.

This paper focuses on the unique requirements, physical attributes, and grinding performance of a developmental grade of CBN designed specifically for the electroplated profile grinding process.

PROFILE GRINDING WITH CBN

Due to the nature of the grinding process itself and also the type of bond system used in the wheels, the requirements of a CBN grit used in an electroplated profile grinding wheel differ from a CBN grit type used in a vitrified-bonded CBN wheel for other applications.

Vitrified-bonded wheels are characterized by high natural porosity and multiple grit layers held together by the glass frit in the bond. Hence, physical properties of a CBN, such as shape and toughness, only partially influence the performance metrics of the wheel, such as ability to maintain form; ability to grind with low power to reduce risk of part burn; and greater intervals between wheel reconditioning. In contrast, electroplated wheels exhibit high abrasive protrusion with 40–50% of the abrasive embedded in a non-porous nickel matrix. This is one of the primary reasons why electroplated wheels work best in a profile grinding set up, as the high level of grit protrusion enables high material removal rates, necessitating fewer grinding strokes per tooth while achieving the required gear form. Because of this, the physical properties of CBN grit have a greater influence on the wheel performance in an electroplated wheel than a bonded wheel.

CBN grits used in an electroplated wheel are typically very “blocky” in shape, with average aspect ratios of the particles lower than 1.50 to promote uniform wheel wear. They are also much tougher than the CBN grits used in a bonded wheel to ensure long wheel life. The range of material removal rates used in profile gear grinding applications results in the CBN crystal wear being more attritious than in other applications. Thus, the CBN grits tend to become progressively dull with wheel usage resulting in an increase in grinding power and the associated risk of thermal damage.

In gear grinding, where thermal damage adversely affects the life and performance of the gear, it is imperative to use a CBN that exhibits a tendency to fracture in small fractions, thus keeping the wheel sharp and free-cutting with a stable grinding power. This property is termed as “microfracturing” capability. It is also highly desirable to have a highly blocky shape to promote uniform wheel wear and achieve consistent gear tooth form from the start to the end of grinding wheel life. Achieving a uniform wheel wear in profile gear grinding is particularly challenging, as the depths of cut and corresponding grinding forces encountered by the grits vary continuously from the top to bottom of a gear tooth flank as cited in previous attempts to model grinding forces in profile gear grinding [2].

The requirements of CBN crystals with uniform shape and lower toughness are truly unique to profile gear grinding. Generally, CBN crystal shapes and toughness are directly correlated i.e. more uniform crystals possess higher toughness and vice versa. Thus developing a crystal with lower toughness and blocky shape presents significant technical challenges. Development of such a novel CBN, referred to henceforth as Developmental CBN A, is reported here along with grinding performance compared to a competitive CBN grade that is commercially available and used in this application.

CBN MORPHOLOGY AND CHARACTERIZATION

Visually, CBN A has much rougher, less well-defined facets than the competitive CBN as seen from SEM...
micrographs in Figure 2. The rough surface morphology helps promote microfracturing ability in the crystals. CBN crystals are generally characterized as a function of their friability using a metric known as toughness index (TI). It is a composite measure that takes into account the hardness, shape and fracture behavior of a crystal. The procedure entails placing a precisely measured amount of CBN in a capsule of pre-defined internal geometry along with a tungsten carbide or steel ball. The closed assembly is vibrated at a set frequency for a fixed amount of time. The contents of the capsule are then separated using a sieve stack and the CBN collected in the sieve stack is accurately weighed. The ratio of the weight of CBN that resisted fracture to the starting weight is reported as the TI. Figure 3 shows that the normalized TI of CBN A relative to competitive CBN A is similar.

EXPERIMENTAL
A typical gear grinding process runs at wheel speeds of 25–30m/s...
with straight oil lubrication and depths of cut of 0.25 mm or lower. A laboratory-scale grinding test configuration was designed to faithfully capture gear grinding conditions as closely as possible.

GEAR GRINDING SIMULATION TEST DESCRIPTION

Profile gear grinding simulation tests were conducted using 1A1 electroplated wheels containing U.S. mesh 170/200 (B91) grit of Developmental CBN A and the Competitive CBN. The wheel specifications are listed in Table 1. Two wheels of each abrasive type were fabricated and tested to assess wheel-to-wheel variability. Through-hardened AISI 4140 steel, which is a commonly used gear material, was chosen as the workpiece material. The 4140 workpieces were chosen to be 3.2 mm in thickness to ensure uniform through hardenability. The specifications of the 4140 workpiece used for the tests are provided in Table 2.

Surface grinding tests were done using a Blohm Precimat 306 surface grinder with a depth of cut of 0.127 mm in upcut mode similar to depths of cuts adopted in profile gear grinding. A wheel speed of 45 m/s was used along with a 5% concentration water soluble oil coolant at a flow rate of 151 liters/min at the entry and exit of cut. This wheel speed was chosen to reduce wheel wear when using a water soluble coolant.

PERFORMANCE METRICS

The two primary metrics by which the performance of a gear grinding wheel is assessed are the risk of thermal damage.

Table 1: Wheel specifications.

<table>
<thead>
<tr>
<th>Wheel type</th>
<th>Electroplated 1A1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel diameter</td>
<td>152 mm (6.0 in)</td>
</tr>
<tr>
<td>Wheel width</td>
<td>12.5 mm (0.50 in)</td>
</tr>
<tr>
<td>Mesh size</td>
<td>US Mesh 170/200 (B91)</td>
</tr>
</tbody>
</table>

Table 2: Grinding test conditions.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Blohm Precimat 306, 15 hp CNC surface grinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grind mode</td>
<td>Transverse (upcut only)</td>
</tr>
<tr>
<td>Test material</td>
<td>AISI 4140 steel; through hardened to 54-56 HRC</td>
</tr>
<tr>
<td>Workpiece heat treating conditions</td>
<td>Austenitized at 1575°F for 45 minutes, Tempered at 335°F for 2 hours</td>
</tr>
<tr>
<td>Wheel speed, $v_w$</td>
<td>45 m/s (9,000 SFPM)</td>
</tr>
<tr>
<td>Depth of cut, $a_d$</td>
<td>0.127 mm (0.005 in)</td>
</tr>
<tr>
<td>Width of cut, $B_d$</td>
<td>3.2 mm (0.126 in)</td>
</tr>
<tr>
<td>Length of cut, $l_c$</td>
<td>305 mm (12 in)</td>
</tr>
<tr>
<td>Specific material removal rate, $Q/w$</td>
<td>6.1 mm$^3$/mm/s (0.75 in$^3$/in/min)</td>
</tr>
<tr>
<td>Table speed, $v_t$</td>
<td>3.8 m/min (150 ipm)</td>
</tr>
<tr>
<td>Coolant</td>
<td>Water soluble oil at 5% concentration</td>
</tr>
<tr>
<td>Coolant flow</td>
<td>151 liters/min at 6.9 bar (40 gpm at 100 psi; entry and exit nozzles)</td>
</tr>
</tbody>
</table>
and loss of form in the ground gear. The occurrence of either on the ground gear would be considered the point of wheel failure. To capture these aspects, grinding performance in the simulation tests was measured as a function of radial wheel wear, surface finish, and specific grinding energy. In addition, the thermal impact of grinding on the workpiece was measured by Barkhausen Noise Analysis (BNA). A wear threshold of 30 mm of wheel wear was chosen to correspond to “form failure.” The radial wheel wear and surface finish were measured by a Hommel Waveline 60 stylus-based profilometer. The wheel wear was replicated in a soft steel coupon wider than the width of grinding as shown in Figure 4. Though the wheel was 12.5 mm wide, the width of cut was maintained at 3.2 mm. Thus only a portion of the wheel width was used for one test. This enabled use of the wheel for a second test if needed. The unused portion of the wheel was used as a reference surface from which to monitor wheel wear. After a pre-determined volume of the material was ground, the entire width of the wheel was used to take a shallow cut in a soft steel workpiece. The resultant wheel trace on the soft steel block was recorded using a stylus-based profilometer. Such a trace provided a measure of the wheel wear relative to the unused (reference) wheel.

It must be noted that for US mesh 170/200, where the average CBN grit size is 91 µm, the nominal coverage of nickel layer for electroplating is 40–50% of the mean grit size. Thus, in theory an electroplated wheel with 170/200 mesh particles is expected to perform predictably to a wheel wear of at least 45 µm. Hence a wear threshold of 30 µm is very rigorous for the purpose of gauging form failure in actual gear grinding process.

The specific grinding energy was quantified by monitoring spindle power using a Hall-effect transducer. The Barkhausen response of the ground workpiece was also recorded. The Barkhausen Noise Amplitude for the 4140 steel workpiece type was optimized to detect grinding burn, as discussed in the following section. The overall effective wheel life was determined by the quantity of material ground at the point of occurrence of either “burn failure” as established by BNA or “form failure.”
BARKHAUSEN NOISE ANALYSIS

Barkhausen Noise Analysis is a non-destructive method of evaluating surface integrity by detecting changes in microstructure in ferromagnetic materials. Barkhausen noise is an inductively measured magneto-elastic signal from ferromagnetic materials, which consists of small magnetic regions called “magnetic domains,” which act like microcosmic magnets. These domains are separated by boundaries known as domain walls; these rotate the magnetic vector of the domains [3].

When an external magnetic field is applied, it initiates an alternate orientation of the magnetic domains by the movement of the domain walls. This change in orientation is stepwise due to irregular changes of magnetization. The removal of the exciting magnetic field causes reversal of domain wall movements, but some domains are not able to take their original dimension and orientation due to a hysteresis phenomenon [3].

This property of ferromagnetic materials can be taken advantage of by applying an alternating current, which would result in back and forth movement of the domains walls, which can be measured and expressed as Barkhausen Noise Amplitude.

BNA OPTIMIZATION PROCEDURE

Several workpiece properties such as the chemical composition, heat treating methods, and conditions influence a material’s response to Barkhausen Noise Analysis and have been discussed in detail elsewhere [3]. Thus, the excitation field conditions (voltage, frequency, and amplitude filter) have to be optimized for each material type. This was done by selecting workpieces ground with identical test conditions at three different intervals of the test: the start,
the middle, and the end of the test. The grinding energy doubled from the start to the end of the test, which meant that there was strong likelihood of thermal damage to the workpiece at the end of the test. Sample sections from the workpieces were metallographically prepared and etched to detect the presence of burn, which is shown in Figure 5. Workpieces ground at the start of the test showed no signs of burn by etching, while workpieces ground at the middle and towards the end of the test showed onset of burn and rehardening burn. This was also verified by microhardness measurements shown in Figure 6.

It can be seen that workpieces ground at the start of the test underwent softening on the ground surface, whereas workpieces ground at the middle and end of test were harder on the ground surface compared to the bulk hardness of the material.

This was followed by measurement of saturation frequencies at small voltage intervals in the Barkhausen Noise Analysis equipment used. The BNA equipment used was a commercially available unit called...
Rollscan 300 made by American Stress Technologies. The saturation frequencies were collected for each of the three workpieces with typical saturation frequency sweeps similar to the one shown in Figure 7. In Figure 8, the ratios of saturation frequencies of burnt and un-burnt workpieces at different voltages are shown. The voltage where the ratio was largest was selected to provide maximum separation and thus maximum resolution in Barkhausen Noise Amplitude between burnt and unburnt parts. From the ratios and saturation frequencies obtained, the optimized Barkhausen settings for 4140 workpiece were found to be 5V-60 Hz and a filtering range of 70-200 kHz. The Barkhausen noise and etch values obtained for different workpieces using these settings is shown in Table 3.

From Table 3, it is apparent that the BNA value drops with increasing depths of rehardening burn. This is a phenomenon that has also been observed and discussed in other related studies [1]. Due to the nonlinear function of BNA, identifying the occurrence of rehardening burn based on BNA alone is challenging, unless the sequence of grinding of the parts is known. This is addressed by the relationship between the specific grinding energy and BNA, where an increase in specific energy and decrease in BNA correlates with the

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burn layer, μm</td>
<td>--</td>
<td>--</td>
<td>0</td>
<td>2</td>
<td>10.5</td>
<td>6.6</td>
<td>13.7</td>
</tr>
<tr>
<td>Mean BN value, mV</td>
<td>103.7</td>
<td>207.5</td>
<td>261.1</td>
<td>226.2</td>
<td>185.6</td>
<td>183.7</td>
<td>143.0</td>
</tr>
</tbody>
</table>

Table 3: Correlation of BNA and etch measurements.

Figure 9: Correlation between specific energy, BNA, and thermal damage.

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presence of rehardening burn as shown in Figure 9.

However, for practical purposes, the onset of burn is characterized as the point of wheel failure. The thermal damage threshold was set at an average BNA value of 250mp or greater where onset of burn was noticed to occur.

RESULTS AND DISCUSSION
Grinding test results are shown from Figure 10 through Figure 13. In Figure 10, the radial wheel wear data for the two CBN crystal types are shown.

It can be seen that the wheel wear for CBN A is significantly lower than the competitive CBN. In case of the competitive CBN, one of the wheels was tested until the wear limit threshold was reached. However neither of the developmental CBN A wheels reached the wear threshold. This implies that the risk of form failure with CBN A is lower than the competitive CBN. From the wheel wear data, it can also be seen that the performance of the wheels for both the CBN is very repeatable. Therefore, in subsequent charts, data from repeatability tests for each sample are not shown for ease of data interpretation.

Figure 11 shows the evolution of specific grinding energy for CBN A compared to the competitive CBN. The specific grinding energy is a measure of the energy efficiency of the grinding process of the CBN crystal. It can be seen that the specific energy for CBN A was consistently lower than the competitive CBN once the wheel reached a steady state. This indicates that the developmental CBN A exhibits a tendency to microfracture. The resulting sharp wheel requires a lower grinding power.

The fracture sequence of a CBN crystal follows a pattern of microfracture, attritious wear, and macrofracture, where larger fractions of CBN particles are fractured. The attritious wear of the CBN causes wheel loading (adherence of grinding swarf to crystal surface) due to greater frictional energy component caused by wheel dulling. This eventually leads to macrofracture at a specific force threshold depending on the CBN crystal toughness. This is the likely cause for the spike in grinding energy noticed in the middle of the test with the developmental CBN, before recurrence of low grinding power once macrofracture of CBN was noticed. However, even with the spike in specific energy, the BNA was marginally lower than that of the competitive CBN at the point of wheel loading and resultant cyclical power. This indicates that CBN A is capable of dissipating higher energy levels than the competitive CBN before causing thermal damage to the ground part. The evolution of BNA for the competitive CBN follows...
the evolution of specific energy, which is typical for most CBN grades. This can be interpreted from a surface integrity standpoint as progressively causing more and more thermal damage on the ground parts from the start to the end of wheel life. Thus in a manufacturing environment it would mean that the surface integrity of a gear ground with the competitive CBN at the end of the wheel life will not necessarily be the same as the gears ground at the start of the wheel life. The truly unique nature of BNA evolution in Developmental CBN A means that the surface integrity of gear teeth ground from the start to the end of the test is nearly uniform ensuring tighter quality control and better quality parts produced overall. CBNA ground the equivalent of 35% more parts than the competitive CBN before the onset of thermal damage.

The lower wheel wear already noted in Figure 10 for CBN A, coupled with the improved thermal performance, points to a significant improvement in useful wheel life. In Figure 13, the surface finish data for two CBN grades are shown. It can be seen that the surface finish for both CBN grades are very similar and the progressively improving surface finish is a typical behavior in electroplated wheels.

CONCLUSIONS
The development of a novel CBN for electroplated profile gear grinding and the protocol for a gear grinding simulation test have been discussed. Form and burn failure were simulated...
Results from the gear grinding simulation test conclusively show that the new CBN, referred to here as Developmental CBN A, significantly outperformed the competitive CBN which is known to be widely used in electroplated profile gear grinding on two counts.

• CBNA ground 35% more material before the occurrence of burn failure compared to the competitive CBN while also exhibiting a unique ability to have a near constant BNA value throughout the course of the test. This implies that the new CBN crystal imparts minimal thermal damage to the ground workpiece from the start to the end of wheel life ensuring uniformity in part quality.

• CBN A also had a much lower wheel wear than the competitive CBN due to a controlled breakdown of crystals in the grinding process.

In practical terms, CBN A is projected to increase by 35% the number of gears ground by a single wheel. The low wheel wear, together with the demonstrated superior thermal performance in the grinding process, corresponds to reduced frequency of wheel changes and incidence of scrap parts. The grinding performance of CBN A thus translates into lower grinding costs and improved productivity for the gear manufacturer.