MICROFRACTURING CERAMIC ABRASIVE IN GRINDING

Jeffrey A. Badger, Ph.D.
The Grinding Doc
Austin, Texas USA

ABSTRACT
Microfracturing “ceramic” abrasives have been in common use for 20 years. However, their success has been limited because of a lack of understanding of how they function and in choosing grinding parameters that take advantage of their self-sharpening ability. A study was made into how these abrasives function and into which grinding parameters should be used to achieve optimum results.

INTRODUCTION
Research into new grinding technologies has been ongoing since the first grinding wheels were used thousands of years ago. Figure 1 shows nineteenth-century developers of a new grinding wheel. One of the more recent developments is microfracturing “ceramic-grit” wheels. Microfracturing abrasives were introduced in the late 1980s and now comprise a significant portion of aluminum-oxide abrasives. They go by many common and trade names – Norton SG®, Cubitron®, Norton TG®, “sol gel”, “seeded gel”, “ceramic abrasive” and “sintered abrasive”, among others. Typical blends are 10%, 30% and 50% ceramic abrasive, with the remaining, 90%/70%/50% standard “fused” Al₂O₃ (1). The grain size of the abrasive is well below one micron (1), resulting in an abrasive that is of higher toughness than standard varieties of aluminum-oxide such as white, pink, brown, etc.

This toughness posed special problems when the product was first introduced. Typically, when a wheel salesperson comes in with a new trial wheel, most machine shops and production facilities will adopt the “stick it on and see what happens” approach, meaning they will run with the exact same speeds and feeds as they have been using with their standard Al₂O₃ wheel. The typical result is dulling of the wheel, as the standard parameters, optimized for abrasives such as white alumina, did not produce forces large enough to fracture the tougher ceramic grit. The end-user then decides the wheel is not appropriate for his operation.

The standard advice for ceramic-grit wheels then became to “push it hard”. One grinding brochure states that “feed depth should be increased somewhat” (2).

ELECTRON-MICROSCOPE OBSERVATIONS
During grinding, there are three type of wear: 1) attritious wear, 2) grit fracture, and 3) bond fracture (3). If grinding parameters are sufficiently aggressive (4,5), the amount of attritious wear is mitigated by the grit fracture and bond fracture, so that the dull grits either fracture or fall out, exposing sharp cutting edges.

If grinding conditions are not sufficiently aggressive, the forces acting on the grits are not sufficiently large to fracture either the grit or the bond posts. Here, the grit becomes progressively duller, resulting in excessive rubbing (3), heat generation and grinding temperatures. This is illustrated in Figure 2, an electron-microscope photo of an excessively dull grit in a vitrified-bonded, N-grade wheel (A46NVB).

Figure 1. Early researchers in new grinding-wheel technology

However, no clear guidelines exist as to what these values should be and how to find them. This paper attempts to rectify that situation. It also discusses the differences between the two major types of ceramic abrasives.
EXPERIMENTAL

Production tests were done on several machines. The first was a 25 kW Gefra flute-grinding machine, creep-feed grinding 3.125 mm-diameter M2 HSS drills using a 30%-ceramic-grit, 100-mesh, resin-bonded wheel with neat-oil coolant, dressing 30 μm every 11 parts with a single-point diamond. Grinding was done at three different feedrates: \( v_w = 600, 780 \) and \( 960 \) mm/min, giving aggressive values (5) of \( \text{Aggr}=11.2, 14.6, 18.0 \) and specific material-removal rates of \( Q'=12.9, 16.8 \) and \( 20.7 \) \( \text{mm}^3/\text{mm}/s \), respectively \( (v_c=58 \text{ m/s}; a_c=1.292 \text{ mm}; d_0=305 \text{ mm}) \). The second machine was a Normac flute grinder grinding M2 high-speed steel with the same wheel specification. The third machine was an older, hydraulically-driven Junker flute grinder. The fourth machine was a modern Junker flute grinder dressing four flutes with a rough-grinding pass and a finish-grinding pass, with a rough-grinding depth of cut of \( a_u=1.6 \) mm at a wheel speed of \( v_w=50 \text{ m/s} \) \( (d_0=200 \text{ mm}) \) using a 3SG wheel. Relative grinding power was measured by a simple ammeter mounted on the machine or true power was measured with The Grindometer® power meter by measuring voltage in three phases and current in three phases with Hall-effect transducers and rectifying the signal to obtain true power with a sampling rate of 50 samples/second.

Because several of the machines were older and hydraulically driven, general feedrates were calculated by measuring time to traverse the workpiece and are given as a percentage of original value.

Wheel wear was measured using “The No Dress Test” (6), where numerous parts were ground without dressing and the change in part dimension was measured. Oxidation burn (7) was assessed visually.

EXPERIMENTAL RESULTS

Test 1: Wheel Wear and Part Push-Off

Test 1 was done on the Gefra machine using a 3SG wheel. Results of the No-Dress Test are given in Figure 4. The parts were also checked for visible oxidation burn, with black points indicating no visible burn, brown points indicating slight visible burn, and red points indicating severe visible burn. The change in part dimension, \( \Delta h_{\text{part}} \), is a combination of two factors: 1) the wheel wear, \( \Delta R_{\text{wheel}} \), on the portion of the wheel suffering the highest wheel wear, in this case at the bottom of the flute; and 2) push-off, \( \Delta h_{\text{spindle}} \). The push-off will depend on the grinding normal force, \( F_N \), and the machine stiffness, \( K_{\text{machine}} \), according to the relation:

\[
\Delta h_{\text{spindle}} = \frac{F_N}{K_{\text{machine}}}
\]  

(1)

Here the machine stiffness will be a combination of the spindle stiffness, \( K_{\text{spindle}} \), and the part-holder/part stiffness, \( K_{\text{part}} \), according to the relation (8):

\[
\frac{1}{K_{\text{machine}}} = \frac{1}{K_{\text{spindle}}} + \frac{1}{K_{\text{part}}}
\]  

(2)

Copyright © 2011 by ASME
After five parts visual oxidation burn was observed. At part ten there is a steady change in part dimension of about 4 μm/part. The total change in part dimension will be:

\[ \Delta h_{\text{part}} = \Delta R_{\text{wheel}} + \Delta h_{\text{spindle}} \]  

At the slow feedrate (a) (600 mm/min.), we can see that there is a steady change in part dimension of about 4 μm/part. After five parts visual oxidation burn was observed. At part ten the part dimension falls off again and oxidation burn disappears. Then part dimension increases at about the same rate, slight oxidation burn is visible followed by heavy oxidation burn, followed again by a drop in part dimension and another cycle.

This cycling behavior reflects wheel collapse (9), where the wheel progressively dulls, resulting in a large normal force and larger machine push-off until the wheel collapses and machine push-off drops due to the sharper post-collapse wheel. This sharper post-collapse wheel is why oxidation burn again disappears.

Premature collapse of the wheel is usually due to poor wheel self-sharpening (9). Therefore, the feedrate was increased by 30%, to 780 mm/min., to increase the Aggressiveness of the grind (5) to induce either more grit fracture or more bond fracture, or both. The result (b) was a steadier wear profile. It’s interesting to note that the overall change in part dimension did not change much. Therefore, it is expected that the ratio of wheel wear to push-off \( \Delta R_{\text{wheel}}/\Delta h_{\text{machine}} \) would increase, indicating better wheel self-sharpening.

The feedrate was increased again (c), to 160% of the original value. Here the change in part dimension decreased. Typically, a more aggressive grind results in a lower G-ratio and higher wheel wear (4). Therefore, we can assume that \( \Delta R_{\text{part}} \) is increasing as the feedrate increases in spite of the decrease in \( \Delta h_{\text{part}} \).

We can then make an estimate of the wheel-wear portion of the change in part dimension, particularly before wheel collapse. This is given by the gray lines in the figure. Here we can assume that the majority of the change in (c) is from actual wheel wear, and then take a slight decrease in the wheel wear in (b) owing to the smaller chip thickness, and again in (a), giving a much higher proportion in (b) and, in particular (a), for push-off due to larger normal forces. For (a) we estimate a wheel wear of \( 1.0 \) μm/part, for (b) \( 1.17 \) μm/part and for (c) \( 1.21 \) μm/part, with the remainder in each case coming from push-off, \( \Delta h_{\text{machine}} \).

This push-off will vary dramatically based on the sharpness of the wheel. In (a), we can take \( \Delta h_{\text{machine}} \) both before collapse and after collapse, as shown in green. Because wheel collapse is a form of self-sharpening that does not occur around the entire circumference of the wheel, but rather as a loss of several layers of grit in select regions, the wheel has sharpened, but in an odd way, with clusters of dull grits with patches of missing grits. This lack of truth results in a lower specific energy (10), but also gives chatter marks and intermittent push-off when the dull grits are engaged.

Therefore, we can conclude that non-aggressive grinding conditions cause dulling of the ceramic-grit abrasive grains, with negative repercussions in terms of burn and change in part dimension. However, it would be helpful to know what specific speeds & feeds are necessary to avoid this situation.

![Figure 4. Change in part dimension at different feedrates.](image-url)

Copyright © 2011 by ASME
The Three Wear Regimes and The Sweet Spot

Considering that low values of aggressiveness lead to excessive grit-dulling, higher specific energies, poor wheel self-sharpening and more rapid wheel collapse (4,9) – we can create a map of the three regimes of wear: Regime I – the dulling & collapse regime; Regime II – the grit/bond-fracture self-sharpening regime; and Regime III – excessive bond-fracture regime. This map is shown in Figure 5.

Figure 5. The three regimes of grinding.

The maximum chip thickness depends on the machine parameters, the cutting-point density and the ratio of chip thickness to chip width (1). However, the cutting-point density and chip-thickness ratio are constant and cannot be changed by the operator. Therefore, if we focus only on parameters that can be changed by the operator we get the Aggressiveness.

The Aggressiveness, Aggr, in grinding is calculated by (5)

\[
Aggr = 1,000,000 \frac{v_w}{v_i} \frac{a_w}{d_e}
\]

where \(v_w\) is the feedrate, \(a_w\) is the depth of cut, \(v_i\) is the wheel speed, and \(d_e\) is the equivalent wheel diameter. The aggressiveness is simply the factors in the calculation for chip thickness that are under immediate control of the machine operator, with the cutting-point density and chip width ratio (8) removed.

The Wheel Wear Factor is the inverse of the G-ratio. If we plot the Wheel Wear Factor and the specific energy vs. the Aggressiveness we should see a relationship as illustrated in Figure 5. In Regime I, grit-penetration is low and the forces are not large enough to cause either grit fracture or bond fracture. The specific energy is high due to the “size effect” (8). Therefore, we see a combination of low penetration depth causing excessive rubbing and a lack of self-sharpening causing the dull grits to remain in the wheel. The high temperatures may also accelerate the rate of dulling. Self-sharpening is initially poor until the wheel collapse occurs. Then, the wheel consists of clusters of dull grits (9), with portions of the wheel lacking grits, resulting in a pseudo-sharpness in these areas. This is shown in Figure 6. Here overall wheel wear will be high and specific energy will oscillate, which is indicated by the wavy lines.

In Regime II the Aggressiveness is moderate and the forces on the grits are large enough to cause either grit fracture or bond fracture or both, depending on the friability of the grits and the grade of the wheel. Here specific energy will be moderate to low as the grit penetration depth is large enough to form a chip and forces are high enough to cause self-sharpening. Wheel wear will be low as it occurs steadily one grit at a time, not in large layers. The center of Regime II can be referred to as the “sweet spot” of the wheel.

In Regime III the Aggressiveness is high and the forces are high enough to cause either immediate and repeated grit fracture and/or immediate bond fracture. Here the wheel is constantly sharp – as grits do not have time to dull before they fracture or are ripped out of the bond material – and specific energy is low. However, the excessive grit/bond fracture causes rapid wheel wear and the Wheel Wear Factor is high.

The data points in Figure 4a are in Regime I; the data points in Figure 4b are somewhere between Regime I and Regime II; and the data points in Figure 4c are most likely in Regime II. If the feedrate was increased beyond 960 mm/min., the slope of the change in part dimension vs. part number would start to increase again as grit fracture began to dominate. Therefore, it is likely that 960 mm/min. is close to the sweet spot.

However, this optimum feedrate will depend on the other three parameters in the Aggressiveness calculation: the depth of cut, the wheel speed and the effective wheel diameter. Therefore, it is not possible to state that the optimum feedrate for a given wheel/workpiece combination is at a specific feedrate. However, it is possible to find the optimum Aggressiveness value to put the operation in the sweet spot. The Aggressiveness in (c) is Aggr=18, indicating that the optimum Aggressiveness for this wheel is somewhere in this region, or perhaps slightly higher.

Figure 6. Wheel profile after collapse.
Defining Regimes and the Sweet Spot, variation of wheel speed

The second test was done on the same machine as Test 1, but for a different part size. The wheel speed was varied from 82 m/s (standard) to 67 m/s to 49 m/s. Wheel wear measured with The No Dress Test, with a significant number of parts ground in order to differentiate between wheel wear and push-off, and grinding power was measured with a simple ammeter mounted on the machine. Results are shown in Figure 7.

Here we see that wheel wear decreased slightly as wheel speed was decreased from 82 m/s to 67 m/s and then increased drastically when the wheel speed was decreased to 49 m/s. According to equation (4), Aggressiveness increases as wheel speed decreases, meaning the forces acting on the grits will be larger at the lower wheel speed. Considering this, and how the values correlate with Figure 4, it appears that 49 m/s corresponds to Regime III (excessive bond fracture), 66 m/s corresponds to Regime II (grit/bond fracture), and 82 m/s corresponds to Regime I (dulling and collapse). This is corroborated by the power curve. At 49 m/s grinding power is low because the wheel is extremely sharp due to excessive bond fracture; at 67 m/s grinding power is moderately higher as some dulling is allowed to occur before grit/bond fracture occurs; and at 82 m/s grinding power is significantly higher as the wheel is dulling without the assistance of grit/bond fracture.

Figure 7. Effect of wheel speed on power and wheel wear.

Defining Regimes and the Sweet Spot, variation of feedrate speed

The third test was done on the same machine and conditions as Test 2 but by varying the feedrate, from 100% of standard to 125% and then to 142%. Wheel wear via The No Dress Test and grinding power on the ammeter were measured. Results are shown in Figure 8.

When the feedrate was increased from 100% to 125% of standard, wheel wear decreased slightly. Since Aggressiveness is directly proportional to feedrate, this means that the aggressiveness increased. However, wheel wear increased drastically at 142%. This fits the trends given in Figure 5, with 100% corresponding to Regime I (or possibly the leftmost side of Regime II), 125% corresponding to Regime II and 145% corresponding to Regime III.

The power is given in red, with power increasing and then leveling off. However, as the feedrate increases the material removal rate increases. The relationship between power, specific energy and material-removal rate is:

\[ P = e \cdot Q \]  

where \( P \) is grinding power in Watts, \( e \) is the specific energy in J/mm\(^3\) and \( Q \) is the material removal rate in mm\(^3\)/s. Therefore, it is more useful to look at the specific energy. We can obtain a normalized value of specific energy by dividing the grinding power by the feedrate to get the values given in green.

Here we see that specific energy does not change significantly from 100% to 125%, and then decreases at 140%. This, coupled with the fact that wheel wear did not significantly change between 100% and 125%, indicates that both the 100% and 125% points are both in Regime II, and that none of these test results lies within Regime I. In any case, the sweet-spot appears to be somewhat between 100% and 125%.

Figure 8. Effect of feedrate on power and wheel wear.

Optimum Aggressiveness Values

Test 4 was ground at five different feedrates of \( v_\text{f} = 400, 500, 600, 700 \) and 800 mm/min. The power profiles are shown in Figure 9. Here we can see the effect of increasing the feedrate and the Aggressiveness. With increasing feedrate power increased somewhat due to the larger material-removal rate – but not proportionately. Also, at \( v_\text{f} = 400 \) mm/min, power increased from Pass 1 to Pass 2 to Pass 3 to Pass 4, indicating that the wheel was dulling. However, as the feedrate increased, the rate of power increase decreased and eventually steadied at 700 mm/min. At 800 mm/min, the power actually decreased, indicating drastic wheel self-sharpening.
W can obtain a normalized value of specific energy simply by dividing the power by the feedrate. This is shown in Figure 10, plotted vs. Aggressiveness.

A moderate power increase is inevitable and desirable as wheel dulling is inevitable. (If power does not increase or if it drops, then wheel wear is undesirably high.) Based on the rate of increase and the shape of the curve, we can estimate an optimum Aggressiveness of Aggr~20. This agrees with the optimum Aggressiveness found in the previous test, of Aggressiveness slightly larger than 18.

Ceramic-grit friability

Test 5 was done at three different feedrates (100%, 120% and 140% of standard feedrate) for two different flute-grinding wheels. Power on the ammeter and wheel-wear with the No-Dress Test were both measured.

The first wheel was a 70-mesh 3SG Norton wheel in a resin bond. The second wheel was a 70-mesh Noritake wheel using 30% Cubitron grit in a resin bond. Although both wheels used ceramic grit, one used 3M’s Cubitron and the other used Norton SG. Also, the wheels were produced by two different wheel manufacturers, so they were not a truly “like for like” test as the bond formulations were different and the remaining 70% standard, fused Al₂O₃ was unknown. Nevertheless, the test was done as it might give some indication as to the difference in the two different grits. Results are shown in Figure 11.

Hitchiner stated that anecdotal evidence indicates that the Norton SG grit is tougher than the Cubitron grit (1). This may explain the recent introduction by Norton of a less-tough Quantum grit. Also, the author has heard from several different end-users that the Norton grit “needs to be pushed harder” than the Cubitron grit, and that Cubitron “is more forgiving than SG”.

From the wheel-wear profile, we can see that the Regime II Sweet-Spot appears to be at around 120% of standard feedrate, with wheel-wear rising to the right of this point due to bond fracture and wheel-wear to the left rising either due to dulling/collapse or possibly because of softening of the resin bond due to high temperatures caused by high specific energies at low Aggressiveness as seen by Kompella (12). The power rises with increasing feedrate due to the increase in material-removal rate. However, it does not rise proportionately to material-removal rate (dotted line), indicating the “size effect”.

For the Cubitron wheel the situation is somewhat different. Here wheel wear increases with increasing feedrate. This indicates that all three tests were done in Regime III, and that Regime I and Regime II lie to the left of the graph. The power increases with increasing feedrate, but again not nearly proportionately to feedrate. We can assume that wheel wear will begin to rise again as feedrate gets smaller. At what point this occurs is difficult to say, but we venture an estimate at around 70% to 100%.

Again, comparisons between wheels must be made carefully because – even through the grit size and general specification is the same – they were produced by two different manufacturers and, moreover, the type of ceramic grit is only one component.

However, from these results it appears that the Cubitron grit is “more forgiving” or less tough than the Norton SG wheel, and that its optimum Aggressiveness will be at around 75% of that of Norton SG (90% feedrate / 120% feedrate = 75%). This difference is corroborated by Hitchiner, who found that anecdotal evidence suggests that Norton SG grits give a longer life but that Cubitron grits are freer cutting (1).

Considering this, and the difficulty some end-users have had in getting Norton SG to work well, it’s not surprising that Saint-Gobain developed a grit what fractures more easily – named Quantum – and advertises it as “versatile in all low, medium, and high force applications” (13). Also, these results indicate that tougher grains requiring higher Aggressiveness values would need harder bond formulations to prevent bond fracture occurring before grit fracture.

Wheel profiles after the 140% No-Dress Test are shown in Figure 12, top for the Norton SG wheel and bottom for the Cubitron wheel. Here we do not see a lot of wheel dulling, which isn’t surprising considering that both the 140% tests were done in Regime III, the bond-fracture regime.
Figure 11. Comparison of Norton SG & Cubitron wheels.

Also, the wheel looks rather “chewed up”, i.e., there is a lot of created porosity in the wheel, which is not typical in resin-bonded wheels. However, quite a bit of bond material was removed, exposing the grits, which is different than in resin-bonded diamond wheels grinding carbide, where the bond “rises to meet” the grit tips as the wheel wears. This demonstrates that the stringy high-speed-steel chips are adequate for creating porosity at the surface of a resin-bonded wheel.

Figure 12. SEM of wheel surface after No-Dress Tests.

A more typical wheel surface, taken from a wheel used in actual production – which was dressed regularly – is shown in Figure 13. Here we can see there is much less natural porosity.

Figure 13. SEM of wheel surface taken from standard production.

Cubitron vs. Fused Al₂O₃

Surface-grinding tests were done on two wheels produced to the exact same specification and fired at the same time. One grit used 100% fused Al₂O₃ and one wheel used 30% Cubitron and 70% fused Al₂O₃. Grinding and dressing conditions were as follows: \( d_s = 200 \) mm, \( v_s = 36.4 \) m/s, \( a_d = 0.0254 \) mm, \( v_w = 3000 \) mm/min., \( V_{coolant} = 4 \) m/s water soluble, \( w = 9.74 \) mm, \( l = 125 \) mm, \( a_d = 0.025 \) mm, \( a_d/d_{grit} = 10\% \), \( v_d = 20 \) mm/s, \( s_d = 0.35 \) mm, \( U_d = 1.7 \), workpiece=stainless steel. Material removed was calculated as \( V_w \) in \( \text{mm}^3/\text{mm/mm} \), the by the total volume removed per mm wheel width per mm wheel circumference.

Here we can see the power profile in the fused Al₂O₃ increases as the wheel dulls. With the ceramic-grit wheel, power increase is much less. Also, in spite of having lower power throughout, the G-ratio was higher with the ceramic grit than with the white Al₂O₃ wheel owing to the small amount of grit that is lost with grit fracture. The surface finish was somewhat rougher with the ceramic Al₂O₃ wheel because the ceramic-grit wheel was sharper, i.e., fewer dull grits.

With the steady power profile and higher G-ratio, it appears that the ceramic-grit wheel is well-optimized for this operation, i.e., in or close to the sweet spot. If we consider the sweet-spot in the previous two examples using Norton SG wheel – Aggr=20 and Aggr=18-22 range –and that the results from Figure 11 indicate that the optimum aggressiveness of Cubitron is around 75% that of Norton SG. That indicates that for a Cubitron grit, the sweet-spot would be around Aggr=15. This test was done at Aggr=15.6.
I and one end being the excessive grit/bond fracture of Regime III. With the No-Dress Test Results and the power profile plotted together, the sweet-spot will be readily apparent.

The same exercise could be done by increasing the feedrate, which would be the option in machines with fixed spindle rotational velocities, i.e., “fixed RPM” machines. However, the increasing feedrate means that material-removal rate would also increase. Since grinding power is related to material removal rate by specific energy according to Equation (5), the specific energy would need to be isolated by dividing the power by the material-removal rate. However, in some cases material-removal rate is difficult to calculate due to complex geometries or changing contact areas. This doesn’t pose a problem, as we are less interested in the absolute values of specific energy and more interested in the general trends of specific energy with Aggressiveness. Therefore, we can simply divide the grinding power by the feedrate to obtain a normalized value. This is what was done in Figure 9 and 10. Here we see the specific energy starting to level off at Aggr=20, indicating the operation is beginning to move into Regime III.

It was clear that Norton SG was a tougher abrasive than Cubitron as anecdotal evidence suggests. It also appears that the sweet-spot of Cubitron is around 75% the Aggressiveness of the sweet-spot of Norton SG. However, further tests would need to be done to corroborate this, particularly in finer grit sizes. The conclusion that Norton SG was tougher than Cubitron was not surprising. What may be surprising is that this test was successful when comparing wheels produced by two different wheel manufacturers, each of which are using their own bond formulations.

The tests shown in Figure 14, unlike the others, which were done on the shop floor, were done in a controlled laboratory setting. Here we see that the power increased in the ceramic-grit wheel, but not as quickly as in the standard abrasive. This advice is given to end-users who use power-monitoring devices such as The Grinding Doc’s Grindometer or Norton’s Field Instrumentation System (F.I.S.), with instructions to grind so that “power doesn’t increase too fast.” However, it would be beneficial to quantify “too fast”. If we look at the figure, we can see in the well-optimized Cubitron that specific energy increased from 56 to 74 J/mm³ when grinding 1.0 mm³/mm³ of material, or 32%. With the white-Al₂O₃, the power increased from 56 to 112 J/mm³, or 100%. Therefore, a guideline could be drawn to say that power in a well-optimized process should increase by 32%/mm³/mm³, or 32%/mm, using the equation for the rate of power increase (ROPI):

\[
\text{ROPI}=100\%\cdot\left(\frac{\Delta P}{P_i}\right)/V_w
\]  
(6)

Where \(\Delta P=P_{\text{current}} - P_i\) and \(P_i\) is the initial power after dressing. A value of zero would mean no power increase, which would indicate overly Aggressive conditions in all materials except perhaps in materials with very high grindability where wheel dulling is extremely slow (15). Negative values would indicate a decrease in power, which would mean that grinding

DISCUSSION

In terms of wheel wear, ceramic-grit wheels behave the same as fused wheels, with low Aggressiveness causing dulling and high Aggressiveness causing excessive bond and grit fracture. The difference is in grit fracture, where if used correctly the grit will lose only a small fraction of its volume.

Unfortunately, end-users have not had guidelines in how to use them, and the “stick it on and see what happens” philosophy has resulted in unsuccessful use. The instructions to “push it harder” have probably helped in its success, but end-users typically do not have the tools to zone in on the optimum values.

The result given here show the grit can be evaluated with power monitoring and The No Dress Test. However, the end-users needs to know how to interpret the results. A large push-off can masquerade as high-wheel-wear, suggesting to the end-user that he should in fact reduce his Aggressiveness. In such cases, the wheel will eventually collapse and present itself as an under-Aggressive grind with dulling. However, a sufficient amount of material must be removed to show this, which may be numerous parts when grinding small sizes. If not, the user may not be able to differentiate excessive wheel wear with excessive push-off unless power is measured. A wheel with excessive push-off due to dulling will show a large increase in power, whereas a wheel will excessive wheel wear will show a flat or even decreasing power profile as shown in the 800 mm/min. case in Figure 9.

One quick and simple method for finding the optimum Aggressiveness is simply to grind at several different wheel speeds. The general trends are given in Figure 5 and shown by a specific example in Figure 6, albeit with the Aggressiveness axis “flipped”. This method is simple as the specific energy is proportionate to power as the material-removal rate remains constant. Here the end use could choose a low Aggressiveness via a high wheel speed and then continue to drop the wheel speed as watch as power decreases. Then, when power no longer decreases, he has reached the excessive grit/bond fracture region. He can then choose an Aggressiveness just before the power fell to a steady-state value. Also, if the user did a No-Dress Test, he should get a simple U-shaped graph as shown in Figures 5 and 7, with one being the dulling of Regime V' and one being the excessive grit/bond fracture of Regime III.
conditions are too aggressive. However, this would also occur
grinding operations with a moderate Aggressiveness but that
were dressed very dull (14).

Of course, this would depend on the grindability of the
material as some materials have much lower grindability than
others, resulting in a much higher rate of power increase (15),
particularly in high-vanadium high-speed steel grades.
Nevertheless, for a given material, for example the standard
HSS M2, a guideline could be given and measured values
compared to that.

CONCLUSIONS

Ceramic-grit Al₂O₃ is tougher than fused Al₂O₃ and
grinding operations using ceramic-grit wheels must be run at
higher Aggressiveness values to get them to self-sharpen.
Norton SG is tougher than Cubitron and it should be run at 33%
higher Aggressiveness when compared to Cubitron wheels in
order to find the “sweet spot” of the wheel. Power monitoring
and The No Dress Test are simple measurements that can be
made in a production environment that can be used to assess
whether the wheel is in Regime I (dulling and collapse), Regime
II (moderate grit and bond fracture and “the sweet spot) or
Regime III (excessive grit and bond fracture). Ceramic-grit
wheels, particularly Norton SG, are prone to dulling if not run at
sufficiently high Aggressiveness values and result in higher
grinding power, higher overall wheel wear, and higher part
push-off. Guidelines are given for calculating the rate of power
increase for grinding a given amount of material.

ACKNOWLEDGEMENTS

The author would like to thank Tony Hudson at Sutton
Tools, Australia and Luis Cano of Austromex.

REFERENCES

1. Marinescu, I., Hitchiner, M., Uhlmann, E., Rowe, W.,
Inasaki, I., Handbook of Machining with Grinding
2. Grinding of Tool Steel, brochure by Uddeholm.
Wheels: Part I – attritious Wear. Trans ASME J. Eng
Ind., 1971, 933, p. 1120-1128.
thickness in grinding. Annals of the CIRP, 23(2), 1974,
p. 227-237.
5. Badger, J., 2008, Practical Application of
Aggressiveness and Chip Thickness in Grinding. J.
Badger, CIRP 3rd International Conference High
Performance Cutting (HPC), Dublin, Ireland, p. 599-
606.
6. The Book of Grinding, Badger, J., course material to
The Grinding Doc’s High Intensity Grinding Course.
7. Tarasov, L.P., Grindability of Tool Steels, 1951,
Technology, William Andrew.
9. Badger, J., Factors affecting wheel collapse in
10. Badger, J., Murphy, S., O’Donnell, G. The effect of
wheel eccentricity and run-out on grinding forces,
waviness, wheel wear and chatter, International
Journal of Machine Tool Manufacture, 51/10-11,
2011, 766-774.
11. Malkin, S., Guo, C., Grinding Technology: Theory and
Applications of Machining with Abrasives, Second
12. Kompella, S., Case studies in cemented tungsten
carbide grinding, proceedings of Intertech, 2008,
Florida.
13. Norton Quantum for Toolroom Applications, Brochure
Form 8082.
using CBN wheels, 2002, International Journal of
Machine Tools and Manufacture, 42, p. 585-593.
Produced and Powder-Metallurgy High-Speed Steel,
Annals of CIRP, 56/1, p. 353-356.