Superabrasive grinding process improvements via power monitoring

Monitoring spindle power during grinding gives valuable information on the grinding process, which can be used to reduce cycle times, cut grinding costs, compare grinding wheels, troubleshoot grinding problems and choose optimum grinding and dressing parameters. This paper by Dr. **J. A. Badger**.

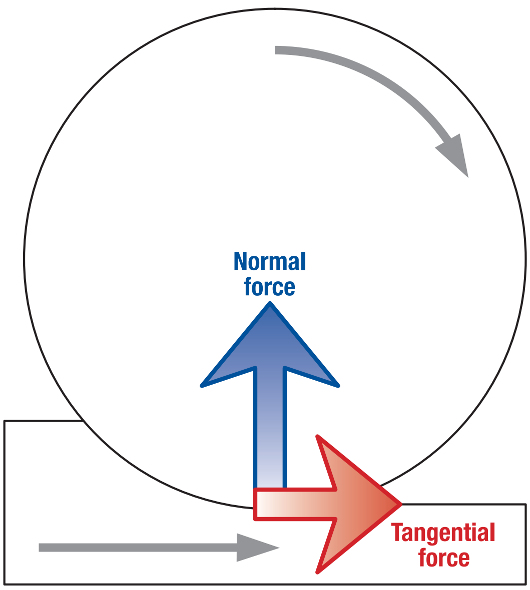

Fig 1 Normal and tangential forces in grinding

Grinding forces are usually divided into the normal force and the tangential force. High normal forces cause erratic part tolerance and self-induced vibration, also known as chatter. High tangential forces cause high heat generation and thermal damage. High resultant forces cause wheel wear. Many laboratory grinding tests measure grinding forces as they give valuable information on the grinding process.

Unfortunately, measuring grinding forces is expensive (a dynamometer costs in excess of $20,000) and extremely cumbersome in real production operations, requiring complex fixturing which must be custom-built for each machine and alters the stiffness of the system and, consequently, the grinding conditions. It is seldom performed on the shop floor.

Measuring grinding power, however, is extremely easy – and gives almost as much information as measuring grinding forces. This paper describes how power is measured and how this signal can be used in a variety of ways to improve the grinding process.

Power = Heat = Temperature = Burn

During grinding, virtually all of the power to drive the spindle motor is converted into heat [1]. For a given set of grinding parameters, heat is directly proportional to temperature [2] according to:

$$\text{Temperature increase (°C)} \propto \frac{\text{partition ratio}}{\text{workpiece thermal property}} \times \frac{\text{grinding power (Watts)}}{\text{contact area (mm}^2\text{)}} \times \sqrt{\frac{\text{arc length (m)}}{\text{workpiece velocity (m/s)}}}$$

The partition ratio, or the fraction of grinding power which enters the workpiece, can be estimated. The contact area, arc length, workpiece velocity and workpiece thermal properties are all known or readily calculated. Therefore, any increase in grinding power will result in an increase in workpiece surface temperature and an increased risk of grinding burn or temperature-induced cracking.

Therefore, monitoring power and, in particular, changes in power with wheel dulling gives information on the risk of thermal damage.

Power = Forces

The tangential grinding force is related to grinding spindle power as [3]:

Grinding power (Watts) = Tangential Force (Newtons) x wheel velocity (m/s)

Since power is directly proportional to tangential force, any increase in tangential force will be accompanied by larger forces acting on the individual grits and, in most cases, higher wheel wear.

Measuring power

Fortunately, measuring spindle power is easy. A typical power-monitoring devices consists of: (1) a power-meter that calculates three-phase power by measuring current with three Hall-effect transducers and voltage with three voltage clamps and then rectifying the signal to give true power in kW; and (2) a data-logger that records the signal from the power-meter.

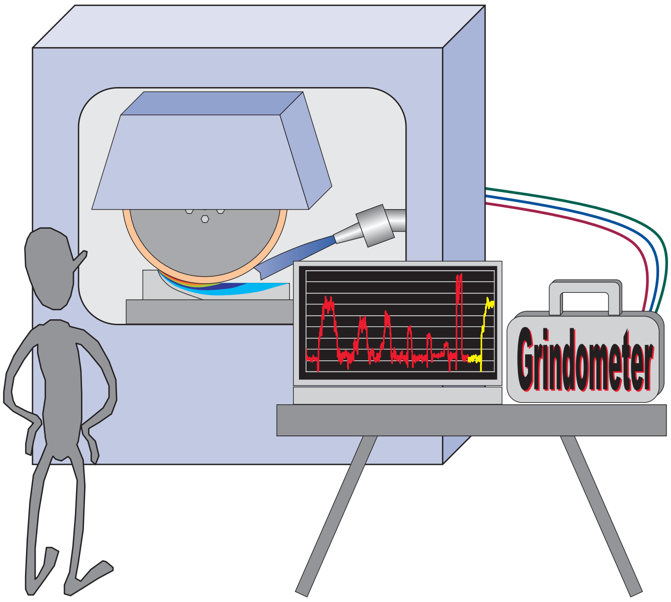

Fig 2 Monitoring the power signal gives valuable information about the grinding process

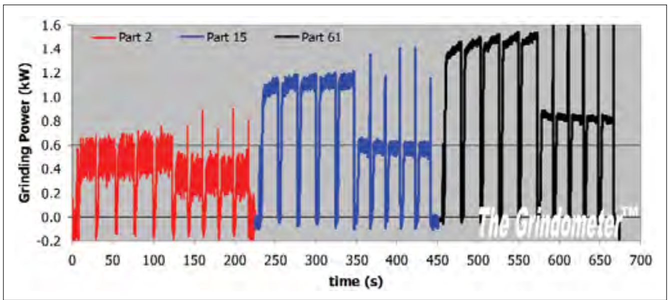

Fig 3 Power profile for flute-grinding of tungsten-carbide endmills

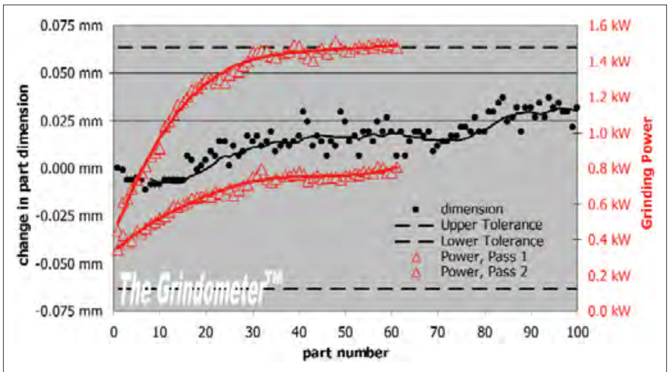

Fig 4 Rough-grinding and finish-grinding power and part-dimension vs. part number for grinding of tungsten-carbide

Typical sampling rates are 10 to 100 samples per second. The signal from the data-logger is either monitored live on a laptop or recorded and downloaded later. The final product is a plot of power vs. time.

Several grinding-wheel manufacturers have developed their own power meters, which their application engineers use at the customer. Norton calls theirs the F.I.S., or Field Instrumentation System. Slip Naxos/Winterthur calls theirs NaxoTech. Camel/C.G.W. calls theirs the G.K.S., or Grinding Knowledge System. I call mine The Grindometer™. Although the components are different, they all do basically the same thing: measure power and output a plot of power vs. time.

Power – gaining it and using it wisely

Once the power profile is obtained, there are numerous ways it can be used to improve the grinding process. Ten of the most useful are given here.

Use 1: Getting a picture of the grinding cycle

Superabrasive grinding processes tend to fall into one of two categories: either (1) the wheel gradually "opens up" with time, with decreasing power and worsening surface finish; or (2) the wheel gradually "closes down" with time, with increasing power and improving surface finish. Whether a wheel "opens up" or "closes down" depends on the wheel type, workpiece type and grinding conditions.

Fig 3 shows the power profile for two-pass grinding of five-flute tungsten-carbide endmills with a resin-bonded diamond wheel on a Rollomatic machine. After truing and sticking, the roughing pass generates about 0.5 kW of power and the finishing pass generates about 0.3 kW (red). As grinding proceeds, the diamond grits begin to dull and the wheel wears, increasing the cutting-point density, both of which result in higher grinding power and usually a better surface finish. As a result, at part 15 (blue) roughing power has increased from 0.5 kW to 1.1 kW (120% increase) and finishing from 0.3 kW to 0.6 kW (+100%). By part 61 (black) power has increased even more, to 300% of its original value. When power gets too high the operator will either true or, more likely, "stick" the wheel.

As part of this assessment, the distance from flute-bottom to flute-bottom was measured for each piece, plotted in Fig 4 with the roughing and finishing grinding power. The change in part dimension is a combination of two factors: (1) wheel wear – as the wheel wears the part dimension increases; and (2) "push off" – as the wheel dulls the normal force increases, resulting in an increase in part dimension.

The combination of grinding power and part dimension gives us a very accurate picture of what is happening in the grinding cycle. In this example we see that grinding power shoots up rather rapidly during the first 20 parts, and then more gradually during the next 40 parts. Also, part geometry, which was set during set-up in the middle of the tolerance range, was about halfway to the upper limit after 100 parts. This baseline can then be used when trying new wheels, new grinding parameters and other process changes.

Use 2: Optimising parameters

The power signal can also be used to choose grinding parameters that give less grinding power (and, therefore, less heat) and a controlled rate of power increase. Speeds and feeds that are too "aggressive" [4, 5] will result in a slow or non-existent increase in power but excessive wheel wear. Speeds and feeds that are too "timid" will result in rapid power increase, meaning the wheel is not self-sharpening. In between these two extremes lies the "sweet spot". The power signal can be used to find this optimum: a wheel that self-sharpens enough to keep the rate of power increase in check but not so much to result in excessive wheel wear.

Fig 5 shows the maximum power in flute-grinding of tungsten-carbide endmills with a resin-bonded diamond wheel on a Rollomatic machine. After truing, power increases as the diamond grits become dull. Eventually power will be too high and the wheel will need to be "stuck" to sharpen it again.

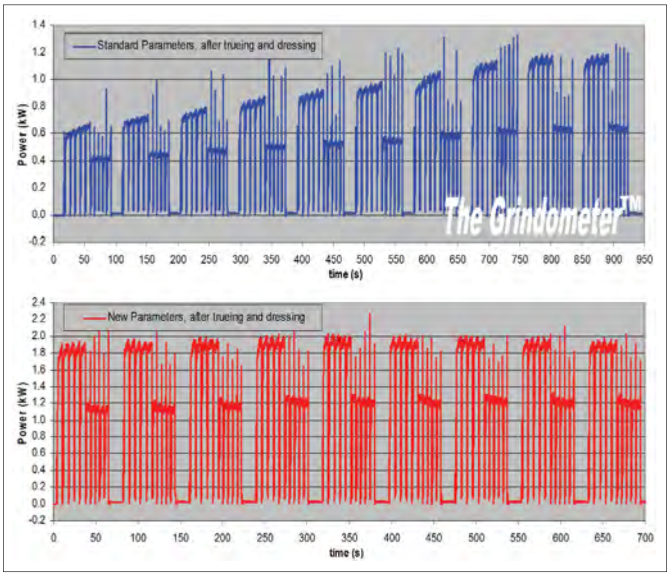

Fig 5 Power profile for two sets of grinding conditions: (1) good aggressiveness and self-sharpening and (2) too aggressive with excessive wheel wear

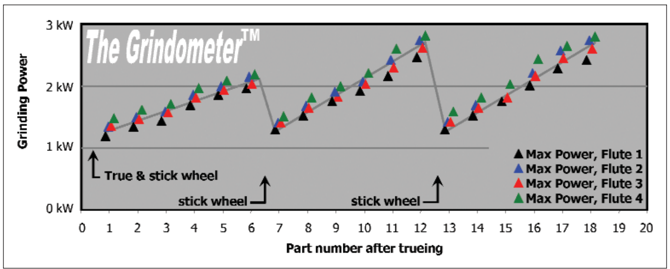

Fig 6 Power increases with wheel dulling, and is mitigated by wheel sticking

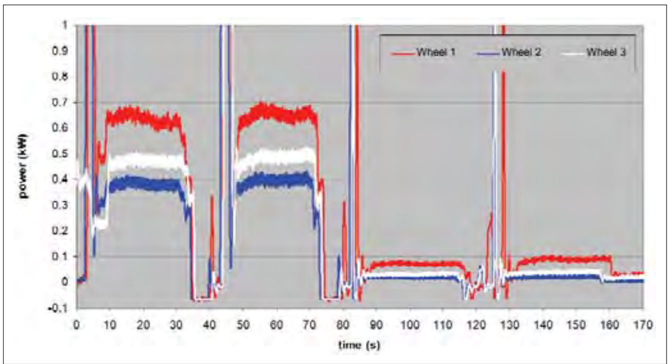

Fig 7 Power profile for three different wheels

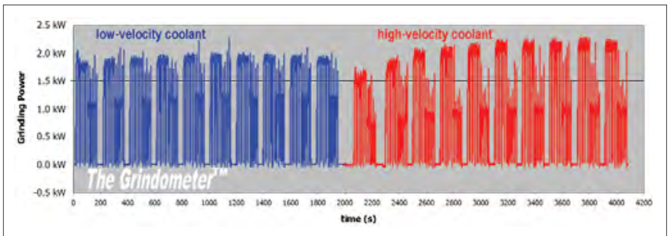

Fig 8 Power signal before and after change to high-velocity cooling system: the improved cooling resulted in less initial power, but less self-sharpening of the wheel; this doesn't mean the improvement should not have been implemented, but that other adjustments must be made to fully optimise the process

In the first case (blue) the wheel is dulling and the power is increasing at a rate that is typical for this operation. In the second case (red), the operator tried new parameters. The new parameters resulted in higher initial power but no increase, meaning wheel wear was almost certainly excessive. The power profile told the operator after only five parts that these parameters were not feasible.

Use 3: Dressing and sticking

Knowing and controlling how the wheel is self-sharpening can help the operator extend the time between truings and between "wheel stickings". In Fig 6, power increases by a factor of nearly two (from 1.2 kW to 2.2 kW) over six parts, and then decreases after wheel sticking. By monitoring power, the operator can determine when sticking is necessary and if he is sticking sufficiently hard to open up the wheel. He can also adjust the speeds and feeds to control the rate of power increase to extend the time between stickings. An operation with too-low aggressiveness will require frequent stickings. An operation with too-high of aggressiveness can go longer between stickings, but usually at the expense of wheel wear, hence requiring more frequent truing.

Use 4: Comparing wheels

One of the greatest benefits of power monitoring is in testing new grinding wheels.

When testing a new wheel, the machine operator typically sticks on a new wheel, runs a few parts, and see how they come out. He may listen to how the machine sounds to see if anything strange is happening. If all seems fine, he'll have to run several hundred parts to see if the wheel is working well.

This unscientific approach is unreliable and wastes time. When looking at the power profile, however, small differences in wheels are readily apparent. Assuming all parameters are kept constant, a wheel that gives more grinding power will, by definition, be more likely to cause thermal damage.

Fig 7 shows the power profile for three wheels when grinding high-speed steel with an aluminum-oxide wheel. Here the operator can see immediately that one wheel is generating much more power than another wheel. This information was used to discard Wheel 1 immediately and focus on Wheels 2 and 3.

Use 5: Process changes

As anyone who has ever tried to improve a grinding process knows, process changes – even obvious improvements – can have insidious side effects. Why? Because grinding has so many interdependent variables that changing just one parameter will affect numerous others.

Fig 8 shows the power profile for grinding tungsten-carbide with a resin-bonded diamond wheel. Originally the process was using low-velocity flood cooling. The cooling system was changed to a high-pressure, high-velocity nozzle arrangement. The immediate benefits were obvious: lower power, less risk of cracking and a longer wheel life. But, the power profile showed that, with the better lubrication, the wheel did not self-sharpen as well, leading to gradually increasing power to values higher than those with the low-velocity cooling. That's not to say this change to high-velocity cooling was not a good one – it just had to be tweaked. In this case, there were numerous tweaks that would have done the job: a softer wheel grade, a lower wheel speed or a faster feedrate.

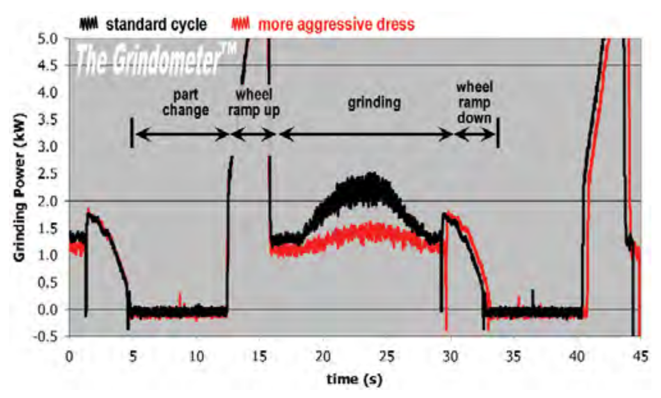

Fig 9 Power profile for grinding of high-speed steel threads with a vitrified-bonded CBN wheel; standard dressing and aggressive dressing

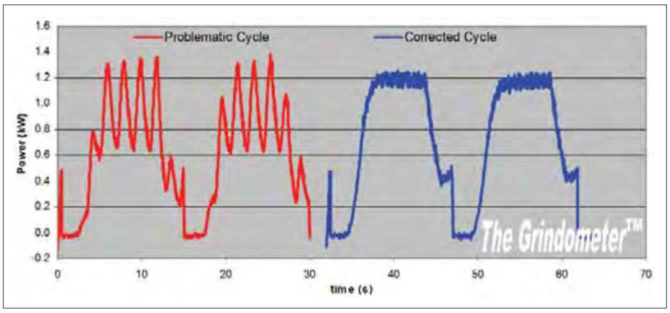

Fig 10 Strange surging phenomenon, before and after corrective action

The power signal helped us identify the need for this small but important tweak right from the beginning, allowing the operator to realise the full benefits of improved cooling while quickly correcting for any unwanted side effects.

Use 6: Cycle mapping

The first step in analysing any grinding cycle, particularly when seeking to reduce cycle time, is to map out the entire cycle. It is important to know how every second of a given cycle is being used.

Fig 9 shows the power profile for thread-grinding of high-speed steel with a multi-rib vitrified-bonded CBN grinding wheel. The goal was to reduce cycle time and, as is often the case, wheel/workpiece grinding time was only a small fraction of the total cycle time – in this case only 32%.

Therefore, energies were focused not in improving grinding, but rather on the ramping up and ramping down that were eating up a huge portion of cycle time. By altering wheel speeds and putting on some extra guards to reduce coolant splashing, ramping was eliminated (not shown here), resulting in a 25% reduction in cycle time, an impossible task if energies were only focused solely on the grinding portion of the cycle.

This technique may not seem high-tech, but it is the first place to start in reducing cycle times. Even high-tech operations have “low hanging fruit”, opportunities to reduce cycle times via simple process changes. This low-hanging fruit is readily apparent from the power profile.

Use 7: Optimising dressing

Changes to dressing parameters can have a profound effect on grinding forces and power and, consequently, the risk of grinding burn, grinding chatter and part tolerances.

Fig 9 shows the change in power with the standard plunge-roll dressing parameters (in black) to the more aggressive dressing parameters (in red). In this case, the speed ratio ($V_{dresser}/V_{wheel}$) was changed from +0.24 to +0.8 in the unidirectional mode, the plunge depth was increased from 0.1 to 0.2 μm/wheel revolution, and the dwell decreased from 40 to 24 revolutions.

The result was a 60% decrease in grinding power and elimination of visible oxidation burn.

Not all changes to dressing parameters result in a reduction in power. The typical methods of assessing whether changes to dressing affect the sharpness of the wheel are to listen to the machine during grinding or to visually examine the parts after grinding for visible oxidation burn or cracks – neither of which is reliable. On the other hand, the power signal tells the user immediately if the change in dressing parameters affected the amount of heat being generated in the grinding zone.

Use 8: Troubleshooting

Identifying and pinpointing problems in the grinding cycle can be a tedious exercise. Often problems are not even discovered until numerous poor-quality parts have been produced. And, even then, pinpointing the cause of the problem can be difficult.

The power signal can be used to help identify the problem and determine if the corrective action was successful. For example, Fig 10 shows the power profile from a Walter machine grinding tungsten-carbide with a diamond wheel. A strange surging of power was seen from the power signal, which did not seem to affect part quality. But the long-term effect of the surging was short wheel life. It was a niggling and difficult-to-identify little problem, which took several tries to correct. But the power signal identified the problem (a truing issue) and told us immediately when the corrective action was successful.

Use 9: Long-term control

A good power monitor can record data at a reasonable sampling rate for over 10 hours. I frequently optimise a grinding process during the day, and then run it over the night shift to ensure the new parameters or new wheel can hold up for a long run. I set the power monitor to run overnight and then check the results in the morning to make sure everything ran ok. It’s also a good way to see if your night-shift machine operators are taking two-hour coffee breaks.

Use 10: Getting fancy – finding the source of chatter

For those who want to get fancy, the power signal can be recorded at a high sampling rate (4000+ Hz) and sent to an FFT (Fourier Transform). Instead of amplitude vs. time, this gives amplitude vs. frequency, and enables the user to pinpoint the frequency of any chatter and, in many cases, the source of the chatter.

Self-induced chatter occurs at the natural frequency of the system. For older, less-stiff machines, this can be around 600 Hz [6], and higher for newer, stiffer machines. Forced chatter usually occurs at lower frequencies. An out-of-true wheel, for example, will “bang” against the workpiece at a multiple of the wheel RPM. A wheel running at 3600 RPM has a frequency of 60 Hz. If the wheel is hitting at two high points, that’s 120 Hz.

If the FFT shows a peak at around 120 Hz, the source of the chatter is an out-of-true wheel. If the FFT shows a peak at 600 Hz, then the source of the chatter is self-induced vibration, which is usually caused by too-high material-removal rates or a dull wheel.

This is a bit more complex than simply looking at the power-vs.-time signal, but shows how a skilled operator can use the power signal to quickly identify and correct problem areas in the grinding cycle.

Other Uses:
Grindability, coolant comparisons, consistency of wheel quality

There are numerous other uses of power. Within a given family of workpiece material, different grades will generate very different amounts of power, and this gives an accurate measure of the grindability of the material [7]. For example, a difficult-to-grind grade of high-speed steel can generate four times the power of an easy-to-grind grade. Companies wanting to assess the grindability of their materials can quickly obtain an accurate ranking by measuring power and wheel wear. Power has numerous other uses, among others assessing the lubricative properties of different coolants and assessing the consistency of grinding wheels.

When to monitor power, when not to bother

When is monitoring power most useful? The biggest benefit comes on very large batch sizes, where the same part geometry is ground over and over hundreds or thousands of times. Here, even minor improvements, say a 5% reduction in cycle time, has lasting, long-term benefits. On smaller batch sizes or one-offs, monitoring power may give some information, but may also be more trouble than it's worth.

Garbage in/garbage out

A power-meter is not an idiot box. For it to be useful, users need to have a good understanding of grinding fundamentals – wheel dulling vs. wheel self-sharpening, dressing the wheel sharp vs. dressing the wheel dull, the effect of grinding parameters on power and heat generation, etc. In other words, it won't give you the answer. But in the hands of a knowledgeable person, it's an invaluable tool that can work wonders in terms of showing you what is happening in the process and allowing you to make significant improvements to the cycle.

To buy or to build

The examples given here are from my Grindometer™. Building your own power-meter is not a difficult job provided you know which components to buy, avoid the usual pitfalls (such as measuring current but not power, hooking it up at the wrong place, or not filtering out noise correctly), and can quickly assemble it and get it running. The total cost of the components is around $5,000. Assembling it, getting it running and getting familiar with it takes a few weeks. I sell my Grindometer™ for $13,500, which includes: (1) all components readily assembled in a portable, briefcase-sized plastic case; (2) a concise instruction booklet on getting The Grindometer™ up and running; (3) The Grinder's Powersheet, a custom-made Excel spreadsheet for making fancy power-vs.-time graphs that can be pasted into reports, (4) The Grinder's Toolbox™, a custom-made spreadsheet for assessing grinding and dressing parameters; (5) attendance of one person to my High Intensity Grinding Course; and (6) two days technical support.

But whether you buy or build, in the right hands a power monitor can yield enormous benefits in terms of cycle-time reduction, cost-savings, part-quality improvements and overall better grinding. ◆

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