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The Great Divide: Grinding in Academia and Production

Jeffrey A. Badger
The Grinding Doc Consulting, Austin, Texas USA
JB@TheGrindingDoc.com

ABSTRACT

Significant progress has been made in the past 50 years in advancing our understanding of the complicated and seemingly random process of grinding, moving it from a sort of black art to an understandable chip-formation process. These advances have been successfully exploited by grain manufacturers, wheel manufacturers and grinding-machine manufacturers in improving their products. However, this knowledge has not successfully been transferred to production companies – those actually doing the grinding – resulting in many companies making the same mistakes and repeatedly reinventing the wheel. This paper explores this deficit, the reasons why, and what needs to be done to rectify this situation, to bridge the gap between the academic world and the practical world of precision grinding.

Keywords: grinding, education, technology transfer.

1. INTRODUCTION

Like turning, milling and drilling, grinding is a chip-formation process [1]. However, because of its seemingly random nature and negative rake angles, grinding is often understood as being "random". Since WWII, significant advances have been made in shifting our understanding of grinding from a random process, or a "black art", to an understandable chip-formation process in the same vein as turning, drilling and milling. The 1950s saw a better understanding of the nature of chip-formation in grinding via the work of Merchant [2] and the translation of this to grinding by Shaw [3], and of the metallurgical problems of thermal damage, or "grinding burn", in hardened steel via the work of Tarasov [4]. The 1960s and 1970s saw huge developments in the understanding of dressing, cooling and grinding and also of thermal models to predict grinding temperatures [5,6]. The 1980s then saw the use of this knowledge to introduce novel hardware and grinding techniques such as creep-feed grinding, continuous dress, and automatic wheel balancing, among others, which acted to increase material-removal rates and part quality.

This knowledge and these developments have been well-utilized by grain manufacturers (examples: controlled grain toughness/friability, controlled angularity/blockiness, microfracturing "seeded-gel"/ ceramic abrasives); by wheel manufacturers (examples: improved bond formulations, hybrid-bond wheels, electroplated bond); and by OEMs (examples: auto-balancing, stiffer spindles, better CNC controls). And the knowledge of efficient coolant delivery to the grinding zone has been established via the work of Webster and others [6].

However, much of this fundamental knowledge has not found its way onto the shop floor where production is taking place. As grinding is a "strategic process" [6] which occurs close to the end of the production chain after much labour has been put into the product, proper grinding can determine the success or failure of a product.

For example, in 1951, Tarasov clarified the vague definition of "grinding burn" – oxidation burn, thermal softening, residual-tensile stresses, and rehardening burn – in hardened steel, describing the metallurgical changes that occur with each and the approximate temperatures where they occur [4]. Sixty years later, however, there is still much confusion about what constitutes "grinding burn", and engineers still rely on visual oxidation to judge whether a workpiece has suffered thermal damage. This is true even in advanced companies.

Figure 1. To this early Parisian knife grinder, grinding was an art form. Unfortunately, in many modern grinding shops, it still is.

Considering that oxidation burn begins at around 250°C, whereas genuine thermal damage typically occurs in the 600 to 1000°C range and may be present in the absence of visual oxidation burn, this can prove dangerous.

Figure 2 shows oxidation burn after thread-grinding. The oxidation burn from thread grinding is on the non-ground surface in the flute-grinding region. Temperatures in this oxidized area were much lower than in the hot-spot region on the thread-ground surface, i.e., “the clean surface”. However, in the thread-grinding region, the oxidation burn was ground away, whereas on the non-ground surface it was not. There is no way to determine if genuine thermal damage is present without using a more involved testing procedure such as polishing/etching, x-ray diffraction, acid cooking, etc. However, many operators and engineers believe that if the tool is clean, it isn’t burned, and if it’s brown and blue, it’s burned. This is false – and risky.

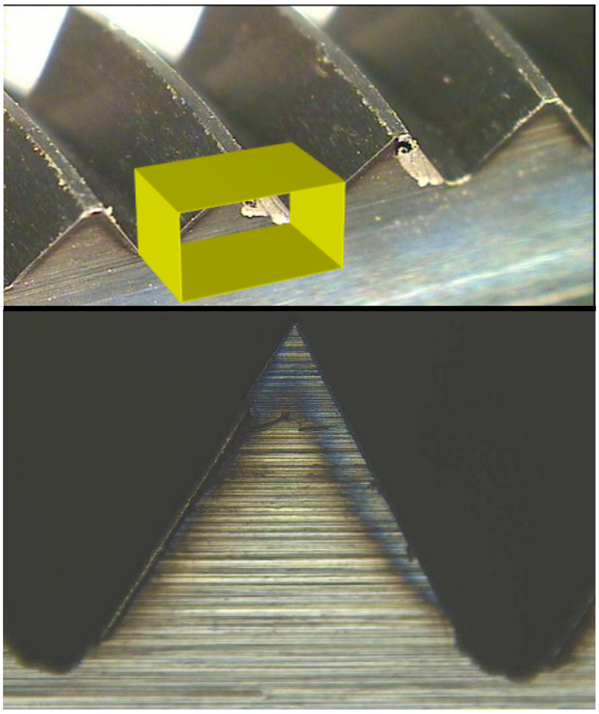

Figure 2. Oxidation burn from thread grinding.

Numerous other examples exist where fundamental concepts in grinding have not made it to engineers in production: a) The coolant velocity should match the wheel velocity [6], with high flowrates not being necessary; b) Rotary dressing in the anti-directional mode will dull the wheel, whereas dressing in the uni-directional mode with speed ratios ($v_{dresser}/v_{wheel}$) greater than +0.8 produce a sharp wheel [5]; c) In single-point dressing, the dressing lead and overlap ratio are far more important in determining wheel sharpness than the dressing traverse speed [5]; d) Superabrasive diamond wheels lose their truth if they are trued on an adaptor, taken off, and remounted on the grinding-machine spindle.

This is basic stuff. But these concepts just haven’t made it to the shop floor, and grinders are learning these concepts “the hard way”: over and over again through trial and error.

2. THE GREAT GRINDING DIVIDE

Since finishing my Ph.D. in 1999 and beginning work as an independent consultant in 2004 under the name “The Grinding Doc”, with a question/answer column in a trade magazine under the same name [7], I have worked for and with numerous companies involved in grinding, have been involved in academic projects, and spent much time on the shop floor in numerous industries. I have visited grinding facilities in 29 countries and have seen low-tech grinding of drill bits and high-tech grinding of artificial-knee implants and turbine blades for jet engines. Regardless of the country or the industry, I see the same situation: many companies do not know the basic concepts of grinding and, more importantly, do not have access to these concepts presented in an easily accessible, practical way.

I have referred to this as “The Great Grinding Divide” – as there is a great divide between the knowledge held in academia and the knowledge held on the shop floor. There are several aspects to it.

2.1. Esoteric – or needlessly complicated?

One reason for *The Great Grinding Divide* is that basic concepts have not been translated into a simplified, useful format that can be quickly utilized by the grinder on the shop floor. Here’s an example:

As opposed to turning, which can be readily modelled in two dimensions with Merchant’s chip-formation model [2], the three-dimensional nature of grinding makes calculating the chip thickness very difficult. Machine operators accustomed to the “speeds & feeds” diagrams in turning are frustrated that such a relationship does not exist in grinding.

The most common equation for maximum chip thickness in grinding, h_m, is some variant of the following [1]:

$$h_m = \left[\frac{6}{C \cdot r} \frac{v_w}{v_s} \sqrt{\frac{a_e}{d_e}} \right]^{1/2} \qquad (1)$$

where C is the cutting-point density, r is the shape factor, v_w is the workpiece velocity, v_s is the wheel velocity, a_e is the depth of cut, and d_e is the equivalent diameter.

However, measurement of the terms C and r is rather subjective. More importantly, the equation is intimidating even to those with higher education who work solely in machining.

However, the equation can be simplified to a “speeds & feeds” equation that uses only the machining parameters that can be varied – depth of cut, feedrate, wheel speed and wheel diameter – and termed Aggressiveness [8].

$$Aggr = \frac{v_w}{v_s} \sqrt{\frac{a_e}{d_e}} \qquad (2)$$

However, this equation still uses variables which must be defined, along with units, and has typical values that are very small, for example Aggr= 1.8×10^{-5}.

Therefore, the equation can be further simplified by multiplying it by a constant of 1,000,000, giving reasonable values.

However, we still have the issue of variables, along with the issue of units and unit conversions. Therefore, we can rewrite this equation in friendlier terms as:

$$Aggressiveness = 16.7 \frac{\text{feedrate in mm/min}}{\text{wheel speed in m/s}} x \sqrt{\frac{\text{depth of cut in mm}}{\text{wheel diameter in mm}}} \quad (3)$$

Here the machine operator can plug in the values from the CNC controls and see what number he obtains.

Typical values for Aggressiveness are between 3 and 60, with lower values for finish-grinding and higher values for rough-grinding. Moreover, each wheel/workpiece/coolant combination will have an optimum Aggressiveness that will place it in the "sweet spot" of the operation, the place where the maximum chip thickness is large enough to form a chip and avoid excessive rubbing and high specific energies, but not so large as to cause excessive wheel wear.

This is an example of taking a complicated concept and modifying it to a simple yet highly useful parameter. Machine operators can identify with the concept of aggressiveness, and there is no need to labour over complex variables and unknown units: it's all given in a format that can be plugged in to a calculator.

I first introduced the concept of Aggressiveness in my *High Intensity Grinding Course* in 2006. Since then, I continue to hear back from attendees saying it is something they use constantly. It has been adopted by others who have an advanced technical background but need a rough-&-ready tool for evaluating grinding parameters [9].

This begs the question: Why haven't similar concepts been translated into similar, easy-to-use techniques? And if they have been, is this information accessible to those on the shop floor?

2.2. No access to the basics

An even simpler formula that's used in calculations in just about every grinding process is the specific material removal rate, Q', calculated by:

$$Q' = a_e \cdot v_w \quad (4)$$

where a_e is the depth of cut measured in mm, and and v_w is the federate measured in mm/s. The specific material removal rate is the total material removal rate per unit width of the grinding wheel.

Unfortunately, many companies are not aware of this calculation, especially if it must be translated into cylindrical grinding.

For example, a company I visited in Europe was unsuccessfully trying to cylindrical-grind hardened steel with a CBN wheel using a "Q-prime" value of 82. An ambitious Q-prime for a CBN wheel on hardened steel would be around 15. This company was trying to make it work with 82, and madly adjusting the dressing and cooling parameters and wheel speed – all to no avail.

The question is: Why was the engineer on the project trying to make a process work with parameters that were outside the practical realm of possibilities for this wheel? The engineer was had a degree in mechanical engineering and was capable of high-level math. However, he did not have access to the concept of specific material-removal rate or the values that were reasonable for cylindrical grinding. He was investing his energies into cooling and dressing, when he should have been investing them into his grinding parameters.

Once the concept was explained to him, he quickly adjusted his process parameters to a more realistic value of Q'. And then he asked, "But how am I supposed to know this stuff? Are there books with this information?"

2.3. *The Literature*

The engineer did have copies of arguably the two of the best books on grinding [1,5]. However, to realize the concept he would have had to: a) find the basic equation for Q'; b) find in another part of the book the conversion from surface grinding to cylindrical grinding for the equivalent diameter; c) make the conversions of workpiece RPM to workpiece surface velocity; and finally d) to know what values of Q' are reasonable.

To a busy production manager, this is too much detective work. If the calculation was available in a neater formula, with units supplied, it would look like this:

> Specific Material Removal Rate in mm^2/s or $mm^3/mm/s$ = 3.14 x workpiece diameter in mm x depth of cut in mm x workpiece RPM / 60. High values for $Al_2 0_3$ = 8, high values for CBN = 15.

This is a calculation the production engineer could make immediately that would tell him if he is in the ballpark of where he needs to be. However, such information is not available in the advanced grinding textbooks. These books are excellent, but they are just not accessible to the layman. A translation of these concepts is needed to put these things in the language the production engineer can quickly understand.

At the moment, the closest thing available is a set of booklets available from a major grinding-wheel manufacturer [9]. To those who are aware of them, these booklets are golden. Most people aren't aware of them.

Also, they are available to the company's customers, not to the wider world of grinding. At the EMO trade show in Germany, I was once offered a bribe from a competitor of the wheel manufacturer: "Listen, these guys are our competitors, but I want to get a complete set of their books. I know you're friends with their head engineer. Can you get me a copy? Don't tell anybody, but I can pay you to get them for me."

People hungry for knowledge on grinding shouldn't have to resort to outright bribery.

2.4. Old Grinders don't die, they just fade away

One reason that companies are lacking people with grinding knowledge is that these people have either: 1) retired, or 2) been laid off during the cutbacks in the 1980s and general cutbacks in the era of lean manufacturing. For example, a 22-year-old engineer hired in 1955 during the post-war boom in manufacturing would have hit retirement age in 1998. Many of these engineers were not replaced. Their knowledge disappeared with them.

In 2002, I visited a multi-national company working in grinding and was impressed by their high level of expertise – several Ph.D.-level engineers and materials scientists and an advanced research program with numerous test machines and measuring equipment.

Six years later, I received a call from them to give my basic three-day course on grinding and some general technical advice on how they can set up a test program. Not a single person from the original 2002 group was now at the company and they had completely lost their technical expertise. They were starting from zero.

Many companies are aware of this knowledge deficit and are looking to rectify it. They then ask themselves: Is it worth my money to rectify it?

2.5. Stringent ROI Criteria

Several times per year I give my three-day *High Intensity Grinding Course*, which covers conventional and superabrasives, dressing, cooling, burr, burn, chatter, choosing grinding parameters, cycle-time reduction and cost reduction. Several grinding-wheel manufacturers offer similar courses and there are courses specialized in particular types of grinding, for example centerless grinding.

The investment for a company to send one person is the $1800 fee plus travel expenses and time away from production. For a company to send one engineer would be an investment of, say, $2500 and four days away from production.

Some decision-makers appreciate this as a long-term investment in the company; some don't. For small, mom-&-pop shops with one grinding machine, it may take time for the knowledge gained in such a course to pay for itself. For companies with 50 grinding machines running three shifts, the return would be quick. Some companies consume $40,000 in grinding wheels a month, with millions spent on labour. Even a slight reduction in wheel consumption (something learned in the course) or cycle time (also learned in the course), will pay for itself almost immediately.

One definition of Lean Manufacturing on a popular web site [10] is "a production practice that considers the expenditure of resources for any goal other than the creation of value for the end customer to be wasteful," with value being defined as "any action or process that a customer is willing to pay for."

Depending on one's definition of "value", this can be a tough sell to some purchasing managers and presidents of companies. I've received emails from numerous engineers saying, "I'm dying to attend your course, but I just can't convince my boss."

Also, in an age when mass quantities of information are readily available on the Internet – and for free – the culture often believes that information on grinding should also be free of charge.

2.6. The Ol' Boys' Club

High-tech advances in grinding continue to be made every year, both in new technologies and new processes and also in developing our understanding of grinding in general. This is evident in any of the technical journals (ASME Journal of Manufacturing Science and Engineering, International Journal of Machine Tools and Manufacture, Journal of Materials Processing, etc.) and conferences (ISAAT: International Symposium on Advances in Abrasive Technology; Intertech: International Conference on Diamond, Cubic Boron Nitride and related materials; etc.). CIRP (The International Academy for Production Engineering) continuously produces excellent work through their rigid, peer-review process.

However, the information presented at these conferences is often, and understandably, at a level that is too high for the layman, and a "translation" must be made to convert the information in these journals and conferences into an easily accessible format. Currently, no such "translation" exists.

Moreover, access to some of these conferences is restricted, or at least difficult. One of my customers, a cutting-tool manufacturer in New England, USA, wanted to attend the 2009 CIRP conference in Boston, 100 km from the company. A paper was being presented on the optimum cutting-edge radius to achieve low cutting forces and long tool life, and how to impart this radius through loose abrasive media. Upon contacting CIRP, the owner of the company was told he would have to pay the full fee of $600 to attend the one presentation and also to find a CIRP member to sponsor his attendance, which involved a lengthy application process. Not being connected with any CIRP members, reluctant to pay the full fee, and not willing to invest the time required for the sponsorship process, the owner of the company chose not to attend.

Fortunately, I knew the speaker and we arranged for dinner and drinks at the local oyster bar for all of us to discuss the matter. Other companies in that situation, however, with no access to members, would probably choose to stay home, missing out on this vital information.

2.7. CBN – Reinventing the Wheel

It is well known there are several requirements to successfully make the shift from Al_20_3 to CBN: 1) CBN requires higher wheel speeds; 2) Compared to Al_20_3, a finer grit size is necessary with CBN to achieve the same surface finish; 3) Single-point dressing is not practical with CBN; 4) Dressing forces are higher with CBN and may require a stiffer dressing spindle; 5) The dressing depth of diamond on CBN is typically 10% of that of Al_2O_3 [11]; 6) Cooling is more important with CBN for it to be economical; 7) The performance advantage of oil over water-based coolants is more pronounced with CBN; 8) Because CBN cannot be "dressed to form", this creates specific considerations in terms of batch sizes; 9) CBN is more prone to loading, and may require a high-pressure cleaning nozzle.

These requirements are well known. However, they are largely unknown by companies who decide to switch from Al_20_3 to CBN. As a consequence, companies the world over "learn the hard way" – and make the same mistakes. They either a) eventually rectify those mistakes and successfully make the switch to CBN, wasting time and resources in the process; or b) go back to Al_2O_3 and decide CBN is not good for this process. In other words, they are reinventing the wheel.

These main points could be gleaned from the literature, but would take time. If a bullet-point list was available – main points when switching to CBN – if would save time and headaches for production engineers. Currently no bullet-point list is available.

Oliveria et. al., in their 2009 CIRP keynote paper "Industrial Challenges in Grinding", outline some of the reasons why CBN has not been fully exploited [12]. The largest factor was cost, as CBN represents a much larger investment in abrasive costs. Second was a "better understanding of the grinding process."

The same can be said of the development of "ceramic grit" ("seeded-gel", "sol-gel", microfracturing grits, trade names: Cubitron® and Norton SG®). These tough grits must be "pushed hard" to get them to microfracture, via a larger maximum chip thickness or Aggressiveness. Unfortunately, many companies that try ceramic-grit wheels simply stick the wheel on, grind with the same parameters as their standard wheel, and experience burn due to dulling of the wheel. In fact, much of my work has been showing companies how to increase the Aggressiveness to higher and optimum values in order to get these abrasives to work the first time.

Again, basic knowledge is not in the hands of the shop-floor grinder.

2.8. *The Grass Is Always Greener "Over There"*

Compared to, say, the computer industry, grinding is a mature technology, and advances come at a slow, steady pace. Many high-tech companies are using grinding machines from the 1970s and doing well with them. Imagine what your colleagues would say if they saw you using a personal computer from the 1970s!

In spite of that, there's still an attitude that the solution to one's grinding problems is to find out some new technology. Also, there are regional perceptions. I am frequently asked by companies in Mexico, "What are the Americans doing?" – as if they have some technology the Mexicans don't have.

In America, I am frequently asked, "What are the Germans doing?" And in Germany I am asked, "What are the Japanese doing?"

In reality, all these companies are using the same machines with the same grinding wheels and the same coolants. I've seen companies in third-world countries doing some excellent grinding and I've seen companies in Japan making silly mistakes. It's a small world, and news of new products travels fast. When a salesman in Germany discovers that this wheel works well on this material on this machine, he emails a colleague in the U.S. with the details.

In a nutshell, companies around the world are doing more or less the same thing, but some of them are doing it better than others. And why? It's not new technologies. It's that they have a knowledge of the fundamentals of grinding: material-removal rates, chip thickness, grit dulling vs. grit fracture, correct grit sizes to achieve a desired surface finish, correct dressing parameters, the importance of coolant velocity over flowrate, etc. – and they're using these fundamentals to gradually improve their grinding process.

2.9. *Chatter: High-tech models, low-tech solutions.*

A prominent example of *The Great Grinding Divide* is chatter in grinding. In the past ten years, numerous papers have published on grinding chatter in the CIRP Annals alone. We now have a high-level understanding of how both forced and self-excited chatter develops, along with specifics for particular types of grinding. We also know strategies for reducing chatter.

An example of a formula given in an excellent academic paper is shown in Figure 3 [13]. It's complicated.

In contrast, the formula which would be valuable to many companies – if they were aware of it – is shown in Figure 4: Simply make sure the ratio of wheel rotational velocity to workpiece rotational velocity avoids an "integer value".

In 2009, I visited a company in Europe battling waviness in cylindrical parts. They had spent weeks fighting it, and based on waviness measurements knew there were wheel diameters that were "danger diameters" when it came to waviness. However, they couldn't piece together why these diameters were dangerous and why they shifted with a change in the wheel speed.

The science behind their dilemma was simple: they needed to avoid harmonics where the imperfect form on the workpiece imparted by the imperfectly round wheel did not "catch the crest of the wave" and repeat this imperfection into the workpiece – i.e., an "integer value". They wanted this imperfect shape to be obliterated – by an "irrational value". This was true both in dressing and in grinding.

And so the solution was simple: develop a basic Excel spreadsheet with the inputs of wheel diameter, wheel surface speed, workpiece diameter, workpiece surface speed, wheel run-out and spark-out time. The outputs were the ratio of wheel velocity to workpiece velocity, to see if an "integer value" was found, along with a rough estimate of the waviness based on the wheel run-out using superimposed sine waves on the workpiece.

$$+kF(s) = (Ms^2 + C_{gm}s + K_{gm}) \times \frac{e^{-\tau_g s}(C_p s + K_w)/(1 - e^{-\tau_w s}) + (C_p s + K_G)(1 - e^{-\tau_g s})}{(C_p s + K_G)/(1 - e^{-\tau_g s})(C_p s + K_W)(1 - e^{-\tau_w s})}$$

Figure 3. Formula used in article on chatter in grinding.

Cylindrical Grinding:

$$\frac{\text{Wheel RPM}}{\text{Workpiece RPM}} \neq \text{an integer } (1,2,3,4,5,6,7\ldots)$$

Rotary Dressing:

$$\frac{\text{Dresser RPM}}{\text{Wheel RPM}} \neq \text{an integer } (1,2,3,4,5,6,7\ldots)$$

Figure 4. Basic rule-of-thumb for eliminating chatter in cylindrical grinding using a rotary dresser.

Figure 5 shows the estimated waviness factor assuming a 3 μm wheel run-out vs. the fractional value in the ratio of wheel RPM to workpiece RPM.

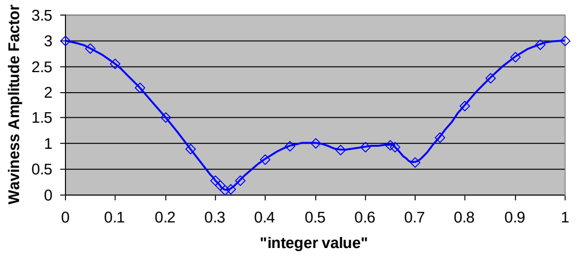

Figure 5. Waviness factor vs. fractional portion of ratio Wheel-RPM/Workpiece-RPM.

The company was then able to use this to avoid integer values (and fractional values). The results are shown in Figure 6. Here we can see a very direct relationship between predicated and measured waviness values. Although *absolute* predicated values were inaccurate due to the unknown value of run-out, using The Galileo Principle described by Shaw [14], the user was able to use the *relative* predicated values to avoid integers and fractions and predict parameters that would give minimal waviness.

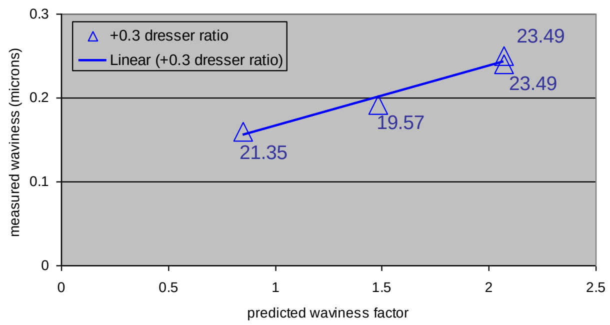

Figure 6. Measured waviness value vs. predicted waviness factor in cylindrical grinding using crude model.

There are sophisticated models of chatter involving finite-element analysis and thousands of lines of code created from thousands of man-hours of development. And to some companies these models are extremely valuable.Here, fifty cells in Excel thrown together in one hour at the hotel bar while snacking on tapas and Rioja were enough to give this company a rough-&-ready method of avoiding high waviness.

How many other companies could benefit from such basic information?

2.10. *Technical conference or infomercial?*

In addition to the academic conferences and journals, there are several conferences that are geared toward people working in production. They are often sponsored by independent organizations, cutting-tool associations, industrial-diamond associations, magazines, etc. The presentations in these conferences are a mixed bag: some remain academic and out of reach to all but high-level Ph.D.s, some are genuinely useful, and some are cleverly disguised marketing ploys to promote a particular company's product or name.

I attended one such conference in 2001. During the question/answer session at the end of the conference, one brave participant stood up and accused the grinding-wheel manufacturer of taking over the conference and doing nothing but promote their products. I have heard this sentiment echoed by others about other conferences.

I've spoken with many production supervisors after such conferences and asked them what they thought. A typical answer is, "Yeah, it was interesting, and I learned a few things. But, when I got back to production tomorrow, I'm not sure I'll be doing anything differently."

3. BRIDGING THE DIVIDE

So what needs to be done to bridge the divide between the academic world and the practical world? Here are some suggestions:

a) Academic organizations and journals should continue with the excellent, refereed articles they publish, but could publish a "layman's summary" of the main findings of the work, with special attention paid to ensuring formulas are presented in words rather than in variables and with units and typical values.

b) Shop-floor grinders and production supervisors must recognize that simply adopting new technology is not enough, they have to take ownership of their grinding operations, which includes the slow, gradual and sometimes tedious acquiring of grinding knowledge.

c) Company owners and presidents much acknowledge that grinding is a "strategic process" essential for the well-being of their company, and must be willing to invest money and time to develop this core competence.

d) Conferences geared toward people in practical production should be refereed, with each speaker's presentation required to answer the question "How can this help my production when I get back to the factory tomorrow?" along with the referee restricting any flagrant promotion of the company or its products.

e) Better communication and cooperation between the OEM, end-user and grinding-wheel producer.

f) Better grinding education focused not only on new technologies, but also on the fundamentals and application of the process.

g) An acknowledgement of production managers and shop-floor personnel that they are responsible for the success of their grinding operations – not the wheel producer or the machine manufacturer – and make the necessary investment in the education and development of in-house grinding experts.

4. CONCLUSIONS

Now that grinding has become a science and not an art-form, and with the loss of much grinding knowledge as the baby-boomer generation retires, a concerted effort is needed to improve the level of fundamental grinding knowledge by those in production facilities actually doing the grinding. It is a slow and gradual process, but an investment that more than pays for itself in terms of lower grinding costs and improved part quality.

5. ACKNOWLEDGEMENTS

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