A Systematic Method for Grinding Wheel Performance Evaluation

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Abstract

Using surface grinding as an example, this paper describes a method for evaluating and optimizing grinding wheel performance by focusing on a few major process elements that can easily be varied and controlled. This work is presented in two parts.

Part one demonstrates techniques for measuring wheel wear and surface finish, and for calculating grinding ratio, specific grinding energy, and grinding efficiency. Commonly used terms such as specific material removal rate (Q') are defined and explained for those new to grinding research. A method is described for measuring the performance of both conventional and superabrasive wheels. The method can be used to compare the relative performance of different wheels or to evaluate the performance of a single wheel.

Part two examines the role that instrumentation and process-monitoring software can play in the evaluation process. It describes frequently used sensors and their characteristics, data collection and analysis techniques, and the software needed to perform the data collection and analysis. Instrumentation available on grinders at ORNL includes plate-type dynamometers for measuring grinding forces, an automatic wheel balancer, vibration and acoustic emission sensors, and sensors for measuring coolant temperature, pressure, and flow rate.

Part I. Evaluating Grind Wheel Performance

Introduction

In order to evaluate and optimize wheel performance, we must focus on the interaction of the grinding wheel with the entire grinding process. A grinding process is much more difficult to control and optimize than other machining processes such as turning or milling because in grinding there are literally thousands of miniature cutting tools acting on the workpiece in a more or less random manner. There are also more process variables in grinding than in most other machining processes, with perhaps a dozen significant variables related to the performance of the grinding wheel alone.

Grinding has traditionally been used for metallic materials such as hardened (> 60 Rc) tool steels, tungsten carbide, super alloys used in the aerospace industry, and ceramic materials such as silicon nitride, silicon carbide, alumina, and zirconia. Grinding may also be the fabrication process of choice for several newer and lesser-known classes of materials such as carbon and metallic foams, bulk amorphous metals (metallic glasses), ceramic-magnets, intermetallics, and composite materials. Anyone faced with grinding these materials should be interested in a cost-effective grinding process while maintaining required dimensional tolerances, surface characteristics, and mechanical properties. Therefore, it is important to be able to monitor and control the major elements of a grinding process and to understand their effect on part quality and cost.

When we speak of *developing* a cost-effective grinding process, we are really looking for a set of operating conditions that will consistently produce parts of acceptable quality at a reasonable cost. Rather than trying to establish the single optimum set of grinding conditions (which probably does not exist) we should seek to evaluate the effects of controllable grinding variables on both cost and quality. There will usually be a tradeoff required to achieve both acceptable quality and cost, since many of the controllable variables in a grinding process act as opposing pairs. In other words, increasing the magnitude of one variable has a similar effect on the process as decreasing the magnitude of some other variable.

Figure 1 shows the major elements for a surface grinding process. The word e*lement* is used to denote any component of the grinding process, and can comprise process requirements or characteristics, workpiece requirements or attributes, parameters that are deliberately varied and used to control the process, or parameters that are held constant. Prior to selecting a fabrication process, the engineer usually knows the workpiece requirements – the desired size, shape, dimensions, tolerances, surface finish, and other elements related to the form and function of the workpiece. The required production rate is also usually known. These elements, combined with the budget, strongly influence the engineer's selection of an appropriate grinding machine, tooling, etc. These process elements are fixed based on design criteria and production requirements.

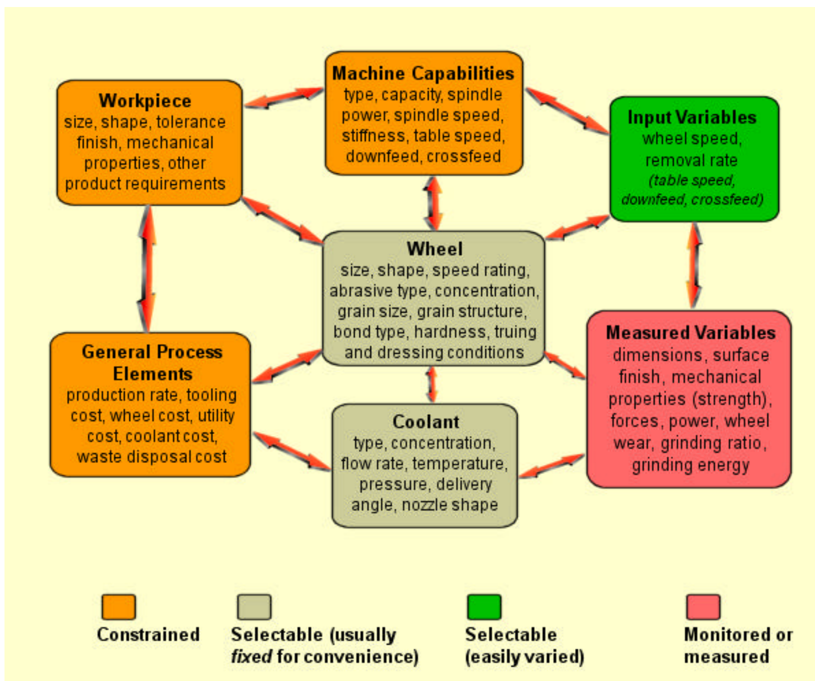

Figure 1. The major process elements for surface grinding can be arbitrarily categorized into groups that are constrained, selectable but fixed, variable, or monitored.

The engineer has more latitude when it comes to the selection of an appropriate grinding wheel, truing and dressing method, and coolant. These choices are based largely on prior experience, machinability handbook data (when they exist), and recommendations from the manufacturers of grinding wheels and coolants. Once these process elements are chosen, they are usually held constant for convenience.

Perhaps the most difficult part of planning the process is making intelligent decisions regarding appropriate values for material removal rate, wheel speed, table speed, downfeed, and crossfeed.

It is a relatively simple matter to choose a conservative set of conditions, try them, and see if they will produce an acceptable workpiece. If only a few parts are being made, it may not be worthwhile to further refine the grinding process. It is highly unlikely that the engineer's arbitrary first choice of operating conditions will generate an acceptable workpiece with maximum wheel life and minimum operating costs. When large production runs are anticipated, there is an economic incentive to optimize the grinding process by maximizing wheel performance.

Maximizing Wheel Performance

Specialized instrumentation such as a dynamometer can simplify the task of optimizing the grinding process by measuring the grinding forces (magnitudes, direction, and frequency content) generated while grinding. However, acceptable results can also be achieved using much less expensive devices for measuring spindle power consumption. Simply stated, our goal is to achieve a good surface finish without chatter or burn, at a material removal rate that will meet or exceed production rates, without wearing the wheel out too quickly. The highest removal rate that meets this goal is the one we want to use in a production application. There will usually be a trade-off between high material removal rate and low wheel wear.

It is assumed that an appropriate grinding wheel has already been chosen based on factors such as the workpiece material, wheel manufacturer's recommendation, prior experience, and cost. The wheel should be balanced, either manually or with the aid of an on-machine, automatic balancer. A well-balanced wheel is required to achieve a good, chatter-free, surface finish. When using an automatic balancer, the balancing cycle should be run with the wheel spinning at its normal operating speed, with coolant on the wheel, but without any table or spindle axis motion. In general, running the wheel at its maximum rated speed or the maximum available spindle speed (whichever is less) is a good starting point. Reducing the speed by a few hundred RPM can make the wheel act softer. The wheel should be mounted and trued according to the manufacturer's recommendations, using a rotary truing wheel, a single point diamond, or a diamond cluster.

Calculating Material Removal Rate

Once the required production rate is known for a process, it is simple to calculate the amount of stock that must be removed from the workpiece in a given amount of time. This number is called the *material removal rate*, and is often expressed in terms of *specific material removal rate*, which normalizes (incorporates the width of the grinding wheel into) the calculation. This allows simplifies the comparison of removal rates for wheels of different widths. Specific material removal rate is abbreviated by the symbol *Q'*, and is expressed in units of $mm^3/s/mm$ or $in^3/min/in$. The specific material removal rate is a fixed quantity, and in surface grinding, it is determined by the table speed and the downfeed. For example, if the table travels at 400 inches per minute and the wheel is fed downward into the workpiece 0.001 inch per pass,

$$Q' = 400\,\mathrm{in/min} \times 0.001\,\mathrm{in} = 0.4\,\mathrm{in}^2/\mathrm{min} \ \text{ or } \ Q' = 0.4\,\mathrm{in}^3/\mathrm{min/in} \ \text{ of wheel width.}$$

Numerous combinations of table speed and downfeed will give the same material removal rate with varying degrees of success. Such things as surface finish, chatter, and spindle power consumption will be affected by the combination of table speed and downfeed chosen. It is straightforward to try differing combinations of table speed and downfeed to determine which combination produces the best results for a given *Q'*.

Determining Grinding Ratio

The *grinding ratio*, or *G-ratio (G)*, is simply a ratio comprising the volume of workpiece material removed divided by the volume of grinding wheel expended (volumetric wheel wear)[1]. If it is possible to grind a very large number of parts on a production floor the volume of workpiece material removed can be easily determined, and wheel wear can be calculated by measuring the change in diameter. However, it may not be feasible to grind a large number of parts. In this case, it is advisable to simulate the actual grinding conditions by grinding rectangular plates that are narrower than the width of the grinding wheel. By setting up the plates as shown in Figure 2, a groove will be worn into the wheel. If the groove is deep enough, a simple depth micrometer can be used to measure the amount of radial wheel wear. However, it is difficult to obtain an accurate measurement in this way. A better method is to replicate the surface of the wheel by grinding a slot in a thin plastic strip. The wheel wear profile can be measured indirectly using a surface-profiling instrument such as the Taylor-Hobson Talysurf shown in Figure 3.

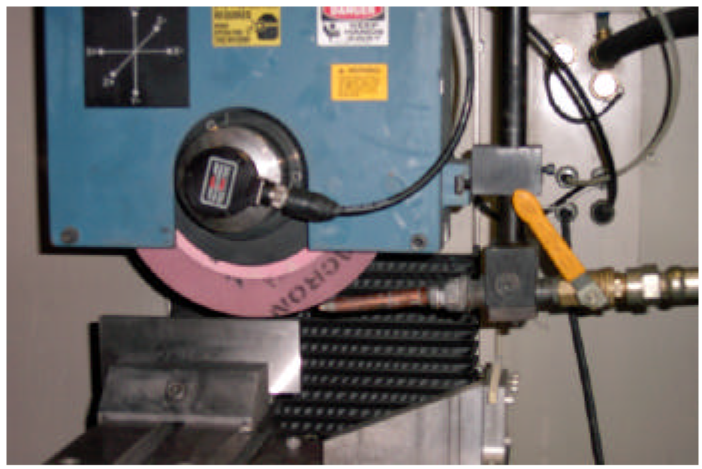

Figure 2. A thin rectangular plate is ground without crossfeed to deliberately generate measurable wheel wear.

In the case of conventional aluminum oxide or silicon carbide grinding wheels, it is usually necessary to grind a minimum of four or five cubic inches of workpiece material in order to generate measurable wheel wear. For diamond or cubic boron nitride wheels, sufficient workpiece material should be ground to generate a wheel wear groove that is at least as deep as one average grain diameter. The amount of workpiece material varies tremendously depending on its composition, hardness, and the grinding conditions used.

Once the G-ratio has been determined for a given set of grinding conditions, at least one additional test should be run under the same conditions to verify the accuracy of the previous test. The original and repeated test results should agree within approximately 15-20 percent. If more than one set of grinding conditions is being tested, the repeated test runs should be randomized. Wider variations in G-ratio test results are not uncommon. They can usually be traced to improper or inadequate wheel truing and dressing prior to the test. However, sometimes the variations are caused by non-uniform layers or other variations in the composition of the wheel itself.

[1] Shaw, Milton C. *Principles of Abrasive Processing*, Clarendon Press, Oxford, 1996, p. 191.

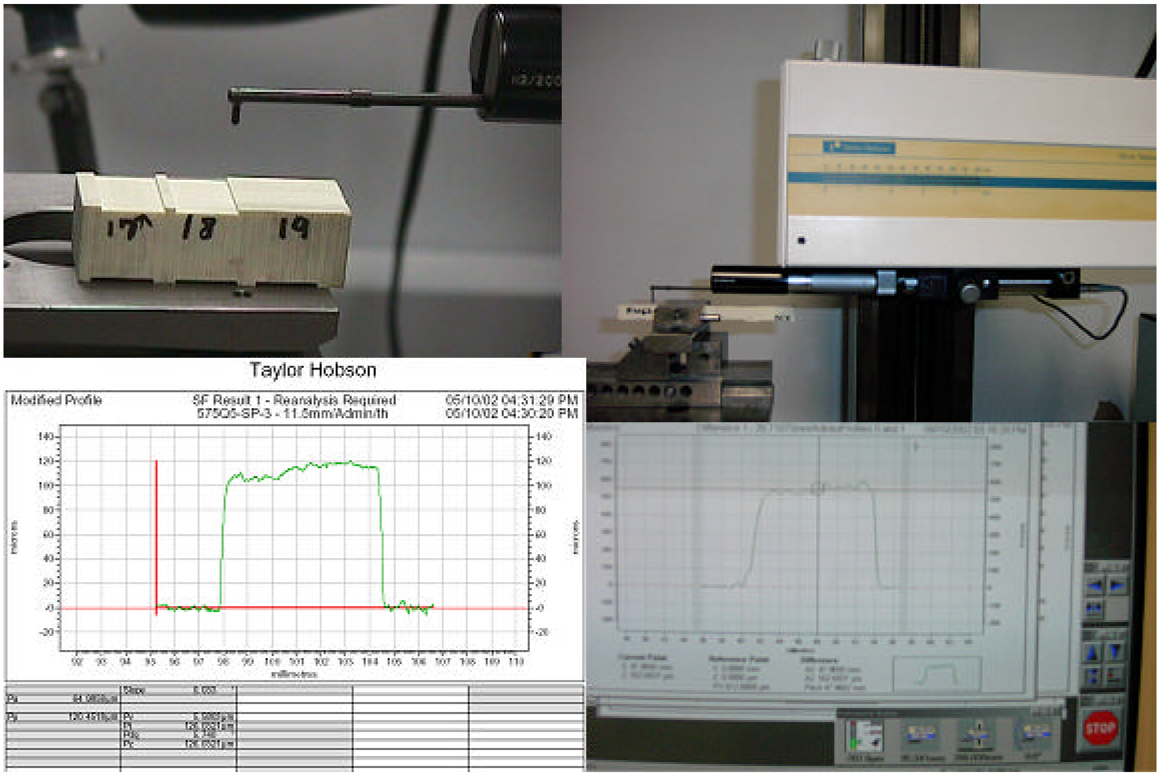

Figure 3. Wheel wear profile is measured on the Taylor-Hobson Talysurf Model 120 surface profiler.

The G-ratio is usually inversely proportional to Q’ as shown by the chart in Figure 4. This example is for a conventional grinding wheel that was used to grind very hard tool steel, and the G-ratio is not particularly impressive, indicating that there are probably better wheel choices for grinding this material. However, the example illustrates the tradeoff between high material removal rate and long wheel life. The process engineer should choose the largest Q’ that will yield an acceptably high G-ratio.

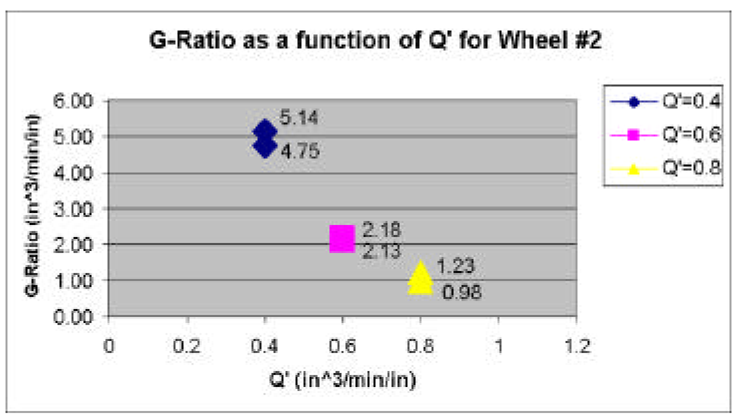

Figure 4. G-ratio is inversely proportional to the specific material removal rate.

The choice is complicated by the fact that the Q’ is determined by the product of table speed and downfeed. For a given Q’ we can specify either a high table speed and a low downfeed (conventional surface grinding), or a low table speed and high downfeed (creep-feed grinding). In general, the optimum combination of table speed and downfeed will need to be determined experimentally.

Calculating Specific Grinding Energy and Grinding Efficiency

In order to further optimize grinding performance, we should consider both wheel life (grinding ratio) and energy consumption (specific grinding energy). *Specific grinding energy (u)* is defined as the amount of spindle power required to remove a unit volume of workpiece material[2]. With all other factors being equal (Q', G-ratio, surface finish, etc.), the operating conditions that give the lowest value for *u* are the most desirable. *Grinding Efficiency (E)* is defined as the grinding ratio *(G)*, divided by the specific grinding energy *(u)*. A high value for *E* is desirable. These two measured process elements are useful for comparing the grinding performance of two or more different wheels, or for evaluating variations in a selectable process element such as wheel speed.

Part II. Monitoring and Controlling a Dynamic Grinding Process with Instrumentation

Introduction

Instrumentation helps us to optimize the grinding process and to establish baseline "signatures" for the grinding process elements, including tangential and normal forces, spindle power, spindle vibration, and acoustic emission. Grinding is a *dynamic* process, meaning that the process elements tend to change with time, even when we try to hold them constant. Coolant concentration changes, abrasive grains get dull and cause the wheel to break down, the surface speed of the wheel may change as the diameter gets smaller, etc. A replacement wheel may behave differently than its supposedly identical predecessor because of variations in the wheel-manufacturing process. Instrumentation helps us to understand when the grinding process is undergoing change and to pinpoint the cause of the change.

Sensor technology is being used at ORNL to evaluate grinding wheel performance. The grinding machines are equipped with a variety of sensors to measure cutting forces, spindle power, vibration, acoustic emission, and other process elements such as cutting fluid flow rate, pressure, and temperatures. The measurements are collected and analyzed to evaluate wheel performance, overall process quality, and ultimately, to recommend grinding parameters and best practices for grinding a variety of different workpiece materials.

Sensors are integrated into the machining systems to monitor the critical energies associated with process quality and wheel performance. Obviously, care must be taken to ensure that the sensors do not alter the static and/or dynamic stiffness characteristics of the grinding machine. This would render results collected from such a system questionable and, in most cases, useless for production machines. The goal is to obtain results that are applicable to industry.[3] However, collecting affordable, reliable, and industrially significant machining data is not an easy task.

To aid researchers, improved techniques are now being employed to help synchronize the machine tool control with the data acquisition process. Machine tool motions and/or commands inserted into the CNC program are being used to trigger data collection events and to automatically prepare data acquisition hardware (reset charge amplifiers, startup, pause, or stop data collection routines, insert markers to highlight events, etc). These techniques simplify the data-analysis process and help to control the volume of data collected throughout a test. More

[2] Malkin, S., *Grinding Technology*, Halsted Press, New York, 1989, p 110.
[3] G. R. Hughes, "Machine Parameter Selections Using Sensor Techniques", Proceedings of a Conference on A Systems Approach to Machining, ASM International, Cincinnati, OH, May, 1993.

importantly, these techniques improve the accuracy, consistency, and overall quality of data by ensuring that measurements always occur at the same point during a test.

"Real-Time" Process Measurements

As stated, various sensor measurements are collected and displayed in "real-time" over the life of the grinding wheel evaluation. Each sensor has unique characteristics and limitations that must be appreciated and understood.

<u>*Spindle Power Measurement:*</u> Spindle power is an extremely valuable measurement that can be correlated with process degradation and overall process efficiency. Spindle power sensors such as the one shown in Figure 5 are very economical (~$1,000.00 US) and easy to integrate into the machine tool. Additional advantages are that they do not alter the machining system in any way nor do they limit the original working envelope of the machine tool.

Figure 5. A sensor for monitoring spindle motor current and phase angle is shown installed in the controller cabinet.

From an analysis perspective, unit power calculations are useful for evaluating the influence of machining parameter combinations (cutting speed, feed, and depths) and helpful in identifying parameter combinations that are more efficient. Spindle power measurements, normalized on a per-revolution-of-the-wheel and/or workpiece basis, are also useful for monitoring, tracking, and detecting changing cutting characteristics over the life of a grinding wheel. However, for grinding machines, spindle power sensors are not well suited for detecting chatter frequencies or other rapidly changing events (frequencies > 60 Hz) because their response time is typically about 15 milliseconds.

<u>*Three-Component Force Measurements:*</u> Plate-type dynamometers are being used at ORNL to measure orthogonal cutting-force components. These systems are composed of piezoelectric crystals that offer a high degree of rigidity (>10,000,000 lb/in) and are ideal for research because they can be configured to accurately measure over a very large force range. They are useful for both small and large force applications. Three charge amplifiers (Kistler Type 5010) are used in conjunction with the dynamometer, as shown in Figure 6. The charge amplifiers are highly configurable and can be used with various plug-in filter modules to filter and enhance signal characteristics. These systems are capable of accurately measuring grinding wheel chatter and other dynamic events associated with the grinding process including wheel degradation and form errors.

The charge amplifiers have a "short," "medium," and "long" time constant selection switch. In the "long" position, drift dominates any time constant effects. As long as the input insulation resistance is maintained at greater than 10^{13} Ohms, the charge amplifier will drift about 0.03

pC/second. Proper cable care is essential to maintain the required resistance. It should be understood that all piezoelectric sensors are susceptible to drift.

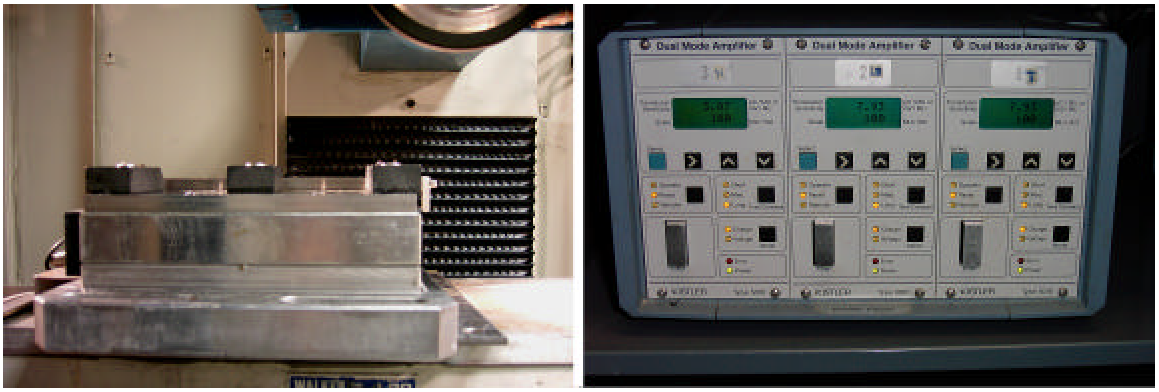

Figure 6. A plate-type dynamometer has been fitted with adjustable clamps for holding a test specimen and is shown mounted atop a magnetic chuck (left). A three-station charge amplifier (right) is connected to the dynamometer to measure 3-component forces.

Resetting the charge amplifiers at the appropriate time, for example, just before entering a cut, is the best way to control the influence of drift. Resetting of charge amplifiers can be done in a number of different ways. In most cases, the technician manually resets the charge amplifiers prior to collecting data or, although not recommended, at a specified moment during the collection process. Limit switches, and other suitable switching hardware, can also be incorporated to automatically trigger resets just prior to entering a cut. Some machine controllers provide special software commands to control relays from within the CNC program. This feature can be used to trigger resets and/or control logic based upon the relay’s current state or change of state. This technique is also quite useful for automatically extracting inertia forces from data generated by plate-type dynamometers that move with the grinding table.

Unlike spindle power sensors, plate-type dynamometers reduce the machine tool’s original working envelope since accurate measurements can only be obtained when the forces are applied within a restricted region about the plate. Although in-the-spindle dynamometers eliminate this constraint, they generally offer less static/dynamic stiffness, especially in directions normal to the spindle axis.

Spindle Vibration Measurement: Accelerometers, strategically positioned on the machine tool, are also useful for detecting grinding wheel chatter, wheel degradation/loading, improper setup, and form errors. These sensors can be easily mounted either with permanent screw-type connections or with magnetic mounts, as shown in Figure 7. However, care must be taken during analysis because these sensors are sensitive to other extraneous input energies from devices such as cooling fans, pump motors, and miscellaneous events such as a passing forklift. Timing pulses, in coordination with accelerometer data, can be used to synchronize acceleration responses with rotational positions along the periphery of the grinding wheel. Characteristics of the time-domain data can be further enhanced by overlaying these measurements, starting at the initial timing pulse, and then averaging the data on a per-revolution-of-the-wheel basis (an analysis technique referred to as time-domain synchronous averaging).

Many grinding machines come equipped with automatic wheel balancers that measure and display current wheel rpm and vibration information. These devices are generally equipped with a serial output device for transferring their display data to another device (such as a data collection system). The data must generally be requested from the device by sending a command string over the serial line and then reading the instrument's response(s). It is difficult to control timing when interacting through a serial interface, due to its relatively slow communication speed. This makes correlation to precise positions/orientations of the grinding wheel virtually impossible. However, it is always desirable to obtain information from an automated balancing device positioned because of its close proximity to the actual grinding contact zone.

Figure 7. The smaller accelerometer on the left is configured for high-speed data collection, while the larger accelerometer provides information to the automatic wheel balancing system.

<u>Acoustic Emission:</u> Acoustic emission (AE) sensors are also very easy to integrate into the machining system through permanent and/or magnetic mounts. These sensors can also be used to measure AE energies through the cutting fluid stream. This technique helps to maintain a constant orientation between the sensor face and the contact zone (AE response is sensitive to input position relative to the AE sensor when it is mounted at some fixed position on the machine tool).

AE RMS profiles are routinely collected at ORNL and have been successfully used to window "in-cut" grinding data. The AE RMS profiles are correlated precisely to wheel-to-workpiece contact and can be used to extract and distinguish "in-cut" and "out-of-cut" data from accelerometer data and other signals where it is difficult to truly ascertain "in-cut" and "out-of-cut" responses.

<u>Software for "Real-Time" Data Capture, Storage and Display:</u> Research grinders at ORNL are equipped with configurable software that is designed to simplify data acquisition and analysis while enhancing the integrity of the collected data sets. The software is written in Labview™, which is a commercially available, graphical programming language that is particularly well suited for data acquisition applications. The software has evolved over several years, and new features have been added to provide a systematic approach to grinding wheel performance evaluation. Some of the more significant features are listed below:

- Measurements are collected and displayed in "real-time."
- Individual plots can be zoomed to further inspect details.
- Storage of each data channel is optional and user-selectable.
- Each channel can be configured to collect data using different sampling rates.

- Calibration settings and sampling rates, as well as other process variables such as fluid flow rate, pressure, and current wheel speed, are stored automatically for every test.
- Notes/observations made during the test can be easily stored and linked to specific test runs using a built-in text editor.
- Previous test notes can be easily reviewed and/or edited.
- Easy file name management/protection, with append and overwrite options, is provided.
- Data collection sessions can be manually started/paused/resumed/stopped.
- External triggers can be used to start/pause/resume/stop data collection sessions. (This feature is ideal for use at the machine tool control when away from the computer.)
- Leaders (markers) can be specified and automatically inserted into data files to visually separate data captures. (This greatly simplifies offline analysis of data.)

The software provides two different methods for synchronizing data acquisition with the machine tool controller. M-codes (M700, M710) are used within the CNC program file to trigger a machine-tool relay that is monitored by the data acquisition software. The acquisition software can be configured to use either of the two methods:

- *Remove Inertia Forces* – This collection mode eliminates inertia forces from the collected force profiles – the charge amplifier is automatically reset, and remains reset, when the relay is energized. The relay is de-energized just before entering the cut.
- *Collect when Relay ON* – This collection mode is ideal for extended tests such as those conducted at ORNL for grinding wheel evaluations. When the relay is energized, the charge amplifier is quickly reset and data begins to flow across the screen and to disk (when data storage is selected). When the relay is de-energized, the data continue to stream across the screen but are no longer written to disk. The sequence is repeated each time the relay is energized. A marker pulse (leader), if specified, is also inserted at this same instant to help simplify post analysis.

<u>*Computer System Requirements:*</u> The software is compatible with National Instruments E-Series DAQ boards and is fully Windows compliant (Win9x, ME, XP, Win2000, NT4.0 or higher). The minimum system requirements are an IBM or compatible PII, 100 MHz, with 64 MB RAM.

Acknowledgements and Conclusions

The Machining, Inspection, and Tribology User Center at the Oak Ridge National Laboratory (ORNL) is a U.S. Department of Energy facility located in Oak Ridge, Tennessee. The user center maintains instrumented grinders, dimensional measuring instruments, and instruments for performing friction and wear studies. The center encourages researchers from U.S. industry and academia to participate in its user program. In many cases, hands-on machining research can be performed at ORNL on instrumented grinding equipment at no cost to the participant. Details of the user program can be found at the following URL: http://www.html.ornl.gov.

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