H. Low-Cost Manufacturing of Precision Diesel Engine Components

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Contractor: Oak Ridge National Laboratory, Oak Ridge, Tennessee
Prime Contract No: DE-AC05-00OR22725

Objectives

- To develop and demonstrate optimized, cost-effective fabrication processes for producing precision components for use in diesel engines.
- To develop and demonstrate optimized, cost-effective, non-destructive testing methods for detecting and preventing machining-induced damage in engine components.

Approach

- Collaborate with universities (e.g., North Carolina State University and University of Michigan) on applied machining research.
- Collaborate with manufacturers of machine tools (e.g., K.O. Lee Company) and manufacturers of consumable materials (such as coolants and grinding wheels) to develop “enabling technology” that can be applied to the process of machining exotic materials.
- Collaborate with manufacturers of diesel engines (e.g., Cummins and Caterpillar), that use our facilities to study the fundamentals of machining processes.
- Continuously improve our instrumentation, data collection and analysis software, and machining, grinding and dimensional inspection equipment consistent with our available budget.

Accomplishments

- Improved the performance of consumable supplies such as the superabrasive grinding wheels that are needed to produce precision engine components.
- Developed nondestructive inspection methods to evaluate machined components for residual stresses and subsurface damage caused by the machining process.
- Investigated machinability issues that have hindered the acceptance of lighter-weight, higher-performance materials in high-volume production applications.

Future Direction

- Continue to develop improved instrumentation and test methodologies for optimizing grinding, turning, milling, drilling, and other machining processes.
- Investigate the aggressive grinding of zirconia with both superabrasive and conventional grinding wheels.
- Address manufacturing issues related to the use of titanium alloys in engine components such as crankshafts, camshafts, valves, and other components where high strength and light weight are issues.
- Investigate the use of machining debris (chips and grinding swarf) as an inexpensive source of structural materials with extremely fine grain size (tens of nanometers).

Introduction

For many materials, such as ceramics and hardened tool steels, grinding is the only practical machining process available to producers of heavy-duty diesel engines. The cost of consumable grinding wheels is a major component in the overall cost of the grinding process. Engine component manufacturers must choose between “conventional” grinding wheels that have a relatively low initial cost but high operating cost, and superabrasive wheels that have a high initial cost but much lower operating cost.

Wheel manufacturers are concerned with producing wheels that are durable, consistent in composition, inexpensive to produce, and capable of producing large numbers of high-quality parts with little variation in dimensions and surface texture. The most important measure of a wheel’s performance relative to these goals is the grinding ratio, often called the G-ratio. G-ratio is simply the volume of workpiece material removed divided by the volume of wheel material consumed, and it is expressed as $G = \frac{v_{part}}{v_{wheel}}$. A very high G-ratio is desirable, which means that the denominator, representing the volume of worn wheel material, will be small relative to the numerator. Because superabrasive wheels tend to wear very slowly, it is often necessary to grind large volumes of workpiece material in order to generate measurable wear. Unfortunately, this is incongruous with a laboratory test environment, where it is desirable to minimize the amount of workpiece material removed so that test times and waste-disposal costs can be minimized. In many cases, a 2-hour laboratory grinding experiment will generate a wheel wear groove that is only a few microns deep. Thus, it is important to develop very accurate measurements of wheel wear to minimize error and ensure repeatability of test results.

Conventional grinding wheels, made from aluminum oxide or silicon carbide in a vitreous bond, can cost anywhere from a few dollars to a few hundred dollars, depending on their size and composition. These wheels typically can be used to produce only a small number of production parts before they need to be reconditioned—a process called truing. The truing process is costly not only because the grinder must stop producing parts while the truing is done but also because truing consumes the grinding wheel at least as fast as the process of producing parts.

Superabrasive grinding wheels are made from industrial-quality diamond abrasive (natural or synthetic) or from cubic boron nitride abrasive in a vitreous, resin, or metallic bond system.

Typically, *G* for a conventional grinding wheel can vary from less than one to a few hundred, depending on the workpiece material and grinding conditions used. For a superabrasive wheel, *G* can range from a few hundred to several thousand, depending on the same conditions. However, *G* does not take into account the cost of lost production time; wheel material lost in the truing process; or the additional time spent in changing wheels, additional inventory costs, etc. Therefore, the decision as to which type of wheel is most cost-effective is not straightforward. There is great interest among wheel manufacturers and end users alike in testing wheel performance on specific combinations of grinding wheels and workpiece materials.

During the past year, three different grinding wheel manufacturers collaborated with ORNL to test new abrasive grain and bond systems and to evaluate the performance of their superabrasive and conventional grinding wheels. In addition, Cummins Engine conducted wheel performance tests at ORNL to evaluate the feasibility of using a single grinding wheel for grinding parts that may be made from either tool steel or zirconia. Their goal is to use a single grinding machine to grind either type of part material without stopping the machine for a time-consuming wheel change.

Approach

ORNL has developed a systematic method for grinding wheel performance evaluation. The method focuses on a few major process elements that can easily be monitored, varied, and controlled; and it attempts to hold the remaining elements constant throughout the evaluation process. Figure 1 shows the major elements for a surface grinding process. The word "element" is used to denote any component of the grinding process; it can comprise process requirements or characteristics, workpiece requirements or attributes, parameters that are

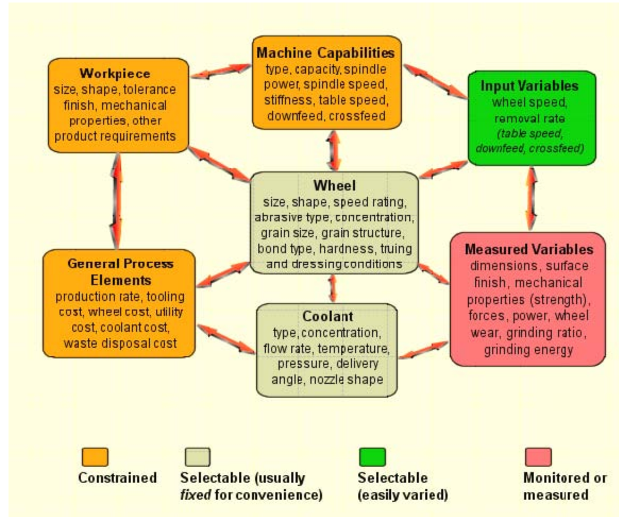

Figure 1. The major process elements for surface grinding can be arbitrarily categorized into groups that are constrained and selectable but fixed, variable, or monitored.

deliberately varied and used to control the process, or parameters that are held constant. Before 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 are usually fixed by design, and they constrain the selection of an appropriate grinding machine, tooling, etc.

The engineer has more latitude with respect 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. A test matrix can then be constructed to systematically vary the remaining process elements, which usually include the material removal rate or the wheel speed. During the grinding tests, instrumentation and process-monitoring software are used to measure and record grinding forces, spindle power, and vibration. These data are stored to disk in a format that can be easily retrieved for later analysis. In addition to these important monitored characteristics, grinding wheel performance evaluation comprises the grinding ratio (G), the surface finish of the ground workpiece, the specific grinding energy (u), and the grinding efficiency (E), all of which can be either measured directly or calculated from the stored data.

In addition to collecting and analyzing on-machine data, it is also necessary to obtain an accurate and repeatable measurement of wear on the surface of the grinding wheel. During the past year, ORNL measured wheel wear with three independent, nondestructive methods and compared the results to determine the most effective method of measurement. These methods incorporated the Taylor Hobson Talysurf surface profiler, the Rodenstock non-contact laser profiler, and the EMD Legend coordinate measuring machine. Each of these instruments evaluates the wear profile using a slightly different method. Our initial results show reasonably good agreement among all three methods, but the Rodenstock is the fastest and simplest instrument to use.

Results

Cummins Engine conducted a performance evaluation test at ORNL to determine if a single grade of superabrasive grinding wheel could be used to grind both hardened 52100 tool steel and zirconia. The grinding wheel was mounted on the grinding spindle, trued, balanced with an automatic balancer, and dressed. (Truing is the process of selectively removing material from the periphery of the grinding wheel to ensure that it has minimal run-out; i.e., the wheel "runs true" to the centerline of the grinding spindle. A wheel that is not properly trued and balanced will generate parts that have a poor surface finish. Dressing is the process of removing a thin layer of abrasive material and bond material to ensure that the abrasive grains are sharp and exposed to the workpiece.)

The primary purpose of the grinding wheel performance evaluation test was to generate measurable wear on the grinding wheel under controlled grinding conditions. The K.O. Lee Vigor creep feed surface grinder was used for the tests, and the machine setup is shown in Figure 2. (The figures shows a conventional wheel—not the actual superabrasive wheel used in this experiment.) The wheel rotated in a clockwise direction at a fixed speed. It was automatically balanced using a microprocessor-controlled balancer. The workpiece was mounted in a vice atop a dynamometer, which was attached to the grinder worktable by an electromagnetic chuck. The worktable reciprocated to the left and right. Coolant was delivered through the nozzle at the right of the wheel, and coolant velocity was adjusted so that it closely matched the wheel velocity. The wheel was moved downward a small amount just before the worktable moved from left to right and was then raised up slightly while the table returned to its starting position on the left.

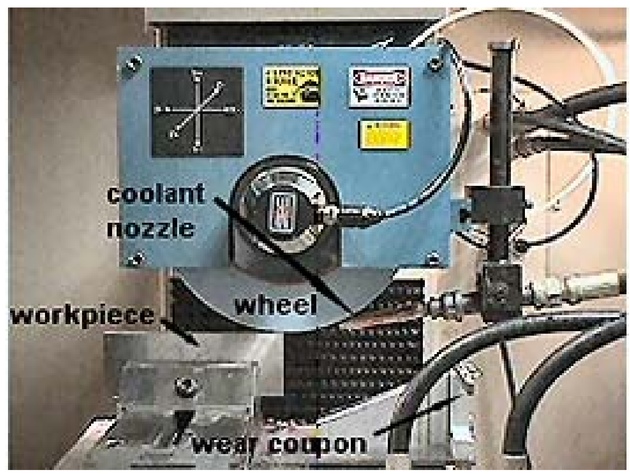

Figure 2. A typical setup for measuring grinding wheel performance on the K.O. Lee creep-feed surface grinder.

This ensured that grinding was done in one direction only; this mode of grinding is referred to as "up" grinding. Tangential and normal forces and grinding spindle power consumption were measured during each grinding cycle. A fixed volume of workpiece material was removed during a predetermined number of grinding cycles.

The wheel was then moved under computer control until it was positioned above the wear coupon. Since the wheel was wider than the workpiece, the center portion of the wheel exhibited wear, while the edges did not. The wheel was then plunged into the wear coupon, and a mirror image of the profile was imparted to the coupon.

Using the Rodenstock RM-600 non-contact laser surface-profiling instrument to scan the wear coupon, a wear profile such as the one shown in Figure 3 was generated. The grinding wheel diameter was known, and the

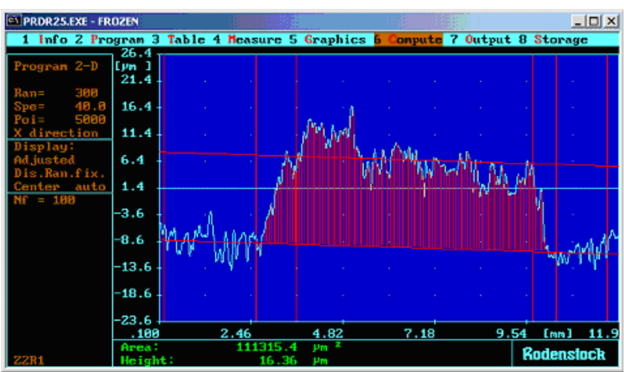

Figure 3. This wheel wear profile was obtained from the Rodenstock laser surface profiler. The step height, which represents radial wear of the grinding wheel, is approximately 16 µm.

area under the wear profile curve was assumed to be uniform over the entire circumference of the wheel. Therefore, the volume of wheel wear could be easily calculated. Finally, the grinding ratio was computed as the ratio of the volume of workpiece removed to the volume of grinding wheel consumed during the test. This sequence was repeated for combinations of three different table speeds, three different downfeeds, and two material types. The wheels were then ranked according to their wear characteristics.

The surface roughness of the workpiece is also an important consideration in evaluating wheel performance. Roughness is strongly influenced by the type of wheel used and the grinding conditions chosen. Surface finishes were measured using the Form Talysurf Model 120 surface profiling and roughness instrument. In addition to being measured for surface roughness, each workpiece is evaluated qualitatively for burrs, evidence of surface regions that have overheated (burning), and repetitive surface imperfections (chatter).

The normal and tangential forces measured during the grinding tests were evaluated to ensure that the wheel performance was consistent throughout the tests and that wheel wear occurred in a more or less linear fashion. The spindle power consumption was measured and recorded during each grinding test. Spindle power can be used to compute the amount of energy required to remove a specific volume of workpiece material. This quantity, frequently referred to as specific grinding energy (u), is another important measure of the overall performance of a grinding wheel. Analysis of the test results is not complete at this time. However, a number of interesting trends were observed. As expected, for 52100 tool steel (hardened to 58-63 Rc), the grinding ratio (G) decreased as the specific material removal rate (Q') increased, as shown in Figure 4. It is not clear whether table speed or downfeed had the greater influence on G. In general, increasing either the table speed or downfeed (while holding the other variable constant) caused a decrease in G.

The results for zirconia were surprising. As can be seen in Figure 5, over much of the range investigated, the G-ratio actually increases as the specific material removal

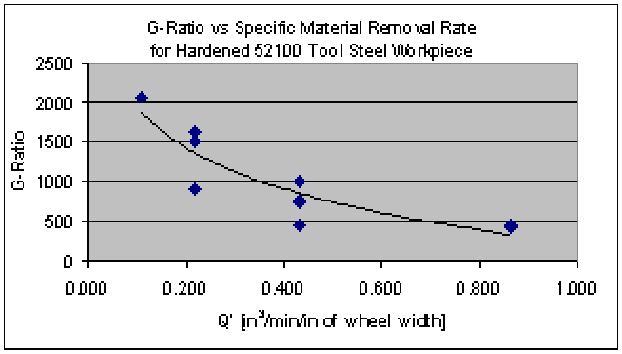

Figure 4. For hardened tool steel, grinding ratio (*G*) is inversely proportional to the specific material removal rate (*Q′*) within the range of table speeds and downfeeds investigated.

rate increases. The trend line shown is a fourth-order polynomial and appears to fit the data reasonably well. Furthermore, the zirconia appeared to grind more easily as table speeds were increased. During the most aggressive grinding test, the zirconia was being ground at removal rates four times as high as the highest achievable rate for tool steel.

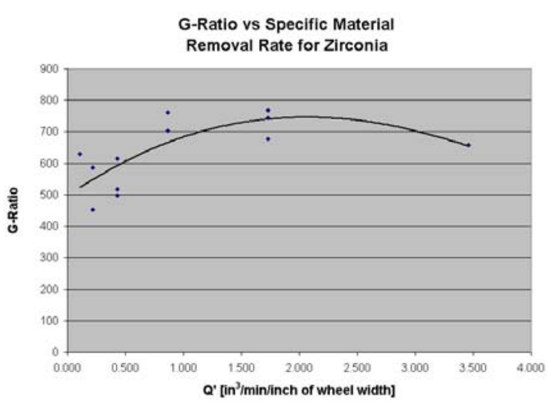

Figure 5. For zirconia, the relationship between grinding ratio (*G*) and specific material removal rate (*Q′*) within the range of table speeds and downfeeds investigated is complex.

Conclusions

Additional investigation of the grinding characteristics of zirconia is warranted to determine an optimum set of grinding conditions. Furthermore, the effect of "aggressive" grinding conditions on mechanical properties and the potential for subsurface damage due to machining needs to be investigated.

Publications/Presentations

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