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# PROCESS DIAGNOSTICS FOR PRECISION GRINDING BRITTLE MATERIALS IN A PRODUCTION ENVIRONMENT <sup>†</sup>

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## ABSTRACT

Precision grinding processes are steadily migrating from research laboratory environments into manufacturing production lines as precision machines and processes become increasingly more commonplace throughout industry. Low-roughness, low-damage precision grinding is gaining widespread commercial acceptance for a host of brittle materials including advanced structural ceramics. The development of these processes is often problematic and requires diagnostic information and analysis to harden the processes for manufacturing. This paper presents a series of practical precision grinding tests developed and practiced at Lawrence Livermore National Laboratory that yield important information to help move a new process idea into production.

## INTRODUCTION

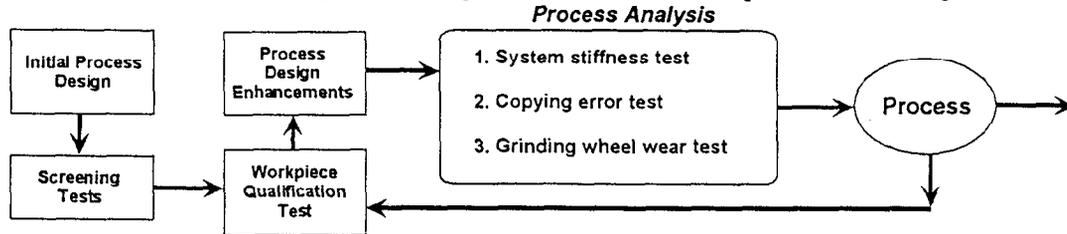
Precision ground components made from materials such as alumina zirconia ( $\text{Al}_2\text{O}_3$ ), silicon nitride ( $\text{Si}_3\text{N}_4$ ), transition-toughened zirconia (TTZ) and alumina titanium nitride (AlTiC) are being exploited for their low density and high wear resistance. Form, finish and strength specifications are now being met in these brittle materials without the need for traditional lapping and polishing operations. Because low damage and shear mode (ductile) grinding processes often appear difficult to control and predict, newly developed production techniques using these methods to replace existing, multi-step processes are frequently dismissed due to poor process understanding. Predicting the economics of candidate processes is, in turn, risky because of limited available information, much of which is generated in laboratory settings. Quantitative information that can be obtained on the shop floor is needed to help engineers build confidence in a candidate process and make appropriate production decisions.

Bringing a precision grinding operation on line requires system feedback related to work piece quality, machine characteristics, and process performance to evaluate the entire manufacturing system including cost. The procedure for implementing such an

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operation often requires iterations based on tests that reveal process performance information, which can be used to further improve the process. Figure 1 shows a simple process development flow chart that typifies the steps required to bring a precision grinding operation on line. The following sections describe aspects of this flowchart and mainly focus on the grinding system diagnostic tests that can help a manufacturing



**Figure 1 – Precision grinding process development**

engineer design and implement a process for production. Among the tests to be described here are a work piece qualification flexural strength test, a grinding efficiency test, a grinding wheel wear (G-ratio) test, and a system stiffness test.

### **INITIAL PROCESS DESIGN**

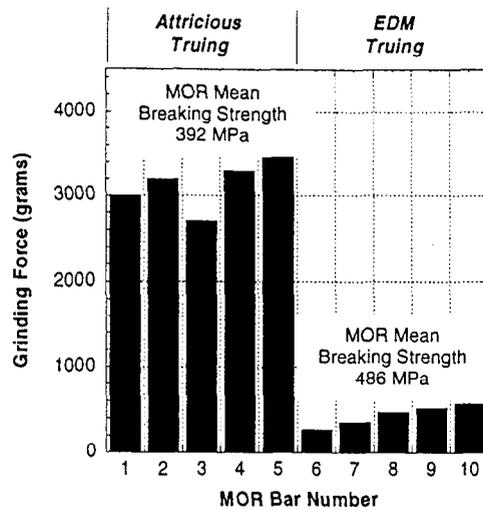
Engineers must be able to predict the cost effectiveness of candidate manufacturing processes through engineering data that comes from reliable tests. These tests can be labor intensive if all of the factors, procedures and products that support precision grinding technology are exhaustively tested. Although the following are tests designed to produce quality data, they are also efficient enough to be used in a screening mode. Screening the range of factors will illuminate the most important ones and reduce the number of actual grinding tests. Most settings can be initially obtained through interaction with hardware suppliers, grinding technicians and published literature. The experiments should be designed to incorporate parameters that encompass the maximum acceptable limits for contour tolerance, surface roughness and sub-surface damage (SSD).

### **FLEXURAL STRENGTH ASSESSMENT**

Using brittle ceramic materials as a direct replacement for metallic components should only be considered if the fracture strength established by the process can be qualified. An estimate of the flexural strength of a critical surface can be made through surrogate four-point bending tests. The modulus of rupture (MOR) for the process can be established by duplicating the work piece surface properties into the tensile surface of MOR bars. The bars are loaded until failure and the breaking strength is recorded. The surface texture and sub-surface damage (SSD) resulting from individual tests will yield different strengths. Attractive processes will yield breaking strengths that approach the theoretical breaking strength for the bulk material. The target strength can be determined by testing a control group of carefully polished bars.

As an example, this test method can reveal the influence of wheel truing methods on fracture resistance. Figure 2 shows the breaking strength of MOR bars produced with a 150um metal bound grinding wheel. The plot indicates EDM truing yields a somewhat lower breaking strength when compared to the control group. For an alternative, attritious truing process the test shows even a further decrease in breaking strength.

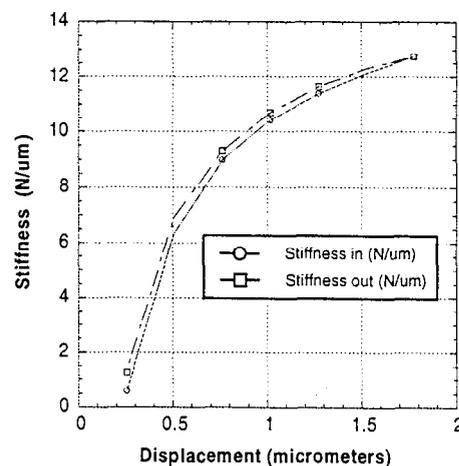
For these tests, the machine tool was also instrumented with a load cell for measuring grinding force. This allows us to see three-way relationships between the method of truing, breaking strength and normal grinding force. The force information is used in further tests to specify tooling and machine characteristics.



**Figure 2** – MOR breaking strength and grinding force as a function of truing method. Control group breaking strength 586 MPa (mean).

### EVALUATING MACHINE TOOL SYSTEM STIFFNESS (“CRASH TEST”)

Machines with high stiffness are required for efficient and deterministic grinding of wear-resistant ceramics. We use the “crash test” to plot non-linear, system stiffness. Again, these evaluations require a load sensing device within the structural loop. The machine and work piece are prepared as if the actual grinding operation were taking place. The grinding wheel is fed or plunged into the work piece to establish conformance, that is, to create a typical contact patch between the grinding wheel and work piece. The machine is readied for the test by de-activating the machine spindle(s) and building tool path program that cycles the in-feed axis into the work piece. The test is performed via CNC in small (sub-micrometer), increasing, incremental steps. The test will show force increase with increasing interference as provided by the CNC command. To avoid damaging the mechanical components, the number of in-feed cycles should be limited. As an example, Figure 3 shows the system stiffness of an ultra-precision grinder as measured by the crash test. The machine has an



**Figure 3** – System stiffness

The machine has an

air-bearing grinding spindle fitted with a 1-mm wide, metal bound "cup" wheel for surfacing 3mm wide AlTiC bars (3mm<sup>2</sup> area of contact).

### Instantaneous Grinding Ratio ("IG-ratio") Test

Candidate processes must consider many options, for example, grinding wheel matrix, grit size, concentration, fluid, and truing techniques. Knowing the rate of wheel wear or grinding ratio (G-ratio = volume of work piece removed/volume of wheel wear) is important for determining the cost-effectiveness of a process. We can quickly determine the rate of grinding wheel consumption as a function of these choices. A test for quickly measuring grinding ratio will allow us to see the G-ratio change and stabilize during use. The diameter of a test piece is reduced by a plunge grinding operation using only a

portion of the grinding wheel circumference as shown in Figure 4. After each reduction the wheel is moved to a vacant area of the test piece and a shallow plunge is performed to provide a full width "witness" band. This band shows the profile of both the used and unused portions of the wheel. Accurate, high-resolution data can be produced from a profilometer tracing of the witness band. The profilometer traces will show the successive wear of the active side of the wheel.

Figure 5 is a plot showing g-ratios that were measured as a function of the material removed after the wheel was dressed. The data was taken during the development of processes for manufacturing silicon nitride work pieces. We used a 300mm diameter, metal bound, 15µm (100 concentration) wheel. The numbers above the lines indicate the in-feed rate in µm/s. The work was performed on a CNC cylindrical grinder fitted with an electro-discharge truing system. Metal bound

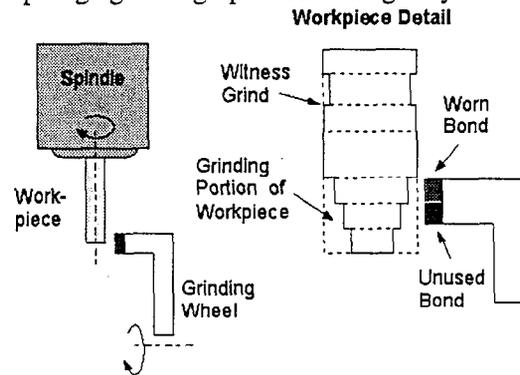


Figure 4 – Grinding ratio schematic

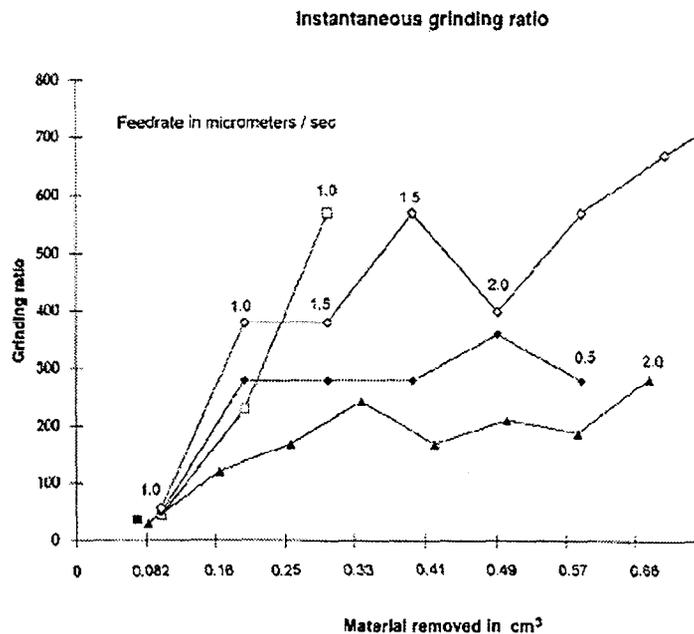


Figure 5 – Instantaneous grinding ratio

grinding wheels that are prepared by EDM truing processes often experience initial, rapid wear, then quickly stabilize during use.

### Cost

We can analyze wheel consumption costs for different operating ranges by using the IG-ratio plot to determine how many units can be produced by the grinding wheel, and how often the profile of the wheel must be restored (trued) to maintain work piece tolerances. The cost of a metal bound diamond grinding wheel is almost entirely due to the diamond. A rough approximation of  $\$67/\text{cm}^3$  ( $\$0.067/\text{mm}^3$ ) can be used. If we have a work piece that 10mm in diameter and 50mm long and we remove 150  $\mu\text{m}$  from the diameter, then we have to remove  $117\text{mm}^3$  of material. If we assume a reasonable G-ratio like 500, then the cost of the abrasive is around  $\$0.016/\text{part}$ . We can clearly see that the costs of processing can overwhelm the cost of tooling, even at low G-ratios.

### PROCESS EFFICIENCY (“COPYING ERROR”) TEST

We need to establish how much time the work piece will spend on the machine. We can easily evaluate the production system for efficiency, that is, how long will it take to produce a surface or surface feature in the work piece. The process efficiency test (“copying error”) determines residual errors in profiling operations. These errors are due to a tightly coupled effect of machine stiffness and grinding efficiency. This universal test can be applied to most material removal processes. The following example uses a “cup” wheel surfacing operation for producing a profile along a 2mm x 50mm bar of AlTiC. Figure 6 shows a profilometer trace of surfaces that were produced with an electrolytically (ELID) dressed “cup” type grinding wheel using a grit size of 1-2  $\mu\text{m}$  at 50 concentration with a metal bond. The wheel is used to produce an initial surface. This surface is finished with several spark out passes to ensure there is negligible residual material. Reference grooves, 1.0  $\mu\text{m}$  deep, are plunged into the initial surface, again, using ample spark-out time. Note the order (1 thru 7) and realize groove 1 and 7 are the first and last of the 7 reference grooves and will only differ in depth by the amount of wear accumulated in the plunge processes. The tool path for the 5 test grinds (2 through 6) will be commanded to remove 0.875  $\mu\text{m}$  of material between sets of reference grooves. The feed rate was 25, 50, 100, 175, and 25mm/min respectively from test 2 through test

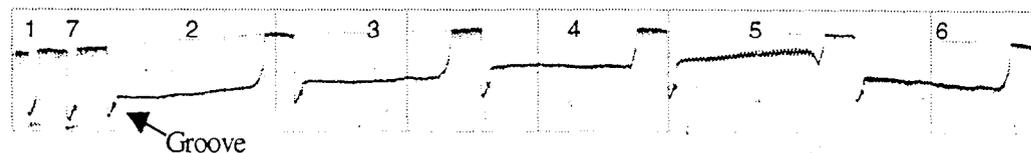


Figure 6 – Process efficiency (copying error) profilometer trace

6. Test 7 is a repeat of test 3 to show the cumulative effect on the wheel. The test piece was removed and inspected with a profilometer. We can see the difference between the commanded depth of cut (DOC) of 0.875  $\mu\text{m}$  and the actual DOC of 0.875, 0.800, 0.625, 0.400 and 0.750 respectively, as a function of feedrate. This exercise can aid the

engineer in determining the efficiency of the process and establish the maximum feed rate or the number passes it will take to produce the desired profile. Roughness plots can also be generated to show the relationship of feed rate vs. surface roughness. The area of contact established by the wheel has a dramatic effect on the efficiency of the process. Again, this is a largely related to system stiffness.

#### **SUMMARY**

Armed with the information from a few practical tests such as the ones presented here, a production engineer can use the acquired process knowledge to make well-informed decisions regarding the implementation of precision grinding equipment and processes in a production environment.