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Investigation of Acoustic Emission for Use as a Wheel-to-Workpiece Proximity Sensor in Fixed-Abrasive Grinding[#]

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Summary

This paper reports on the feasibility of using Acoustic Emission (AE) for sensing the proximity of a grinding wheel to a glass workpiece, both prior to contact and in the early stages of contact. Our measured AE signals indicate that we can track the position of the grinding wheel as it approaches the workpiece through the turbulent coolant layer and then as contact initiates with a workpiece during spherical generation. Our data for the initial contact region is dominated by cyclical bursts of AE that appear to correspond to tool spindle motion errors. Our principal goal is to minimize the time required to 'find the part' without damaging the surface of a brittle workmaterial, i.e. during the transition from a fast approach to the much slower final in-feed required for the grinding operation. Our results also suggest that AE is useful as a gauging signal in determining the position of the grinding wheel with respect to the machine tool.

Introduction & Motivation

The Center for Optics Manufacturing (COM) and the American Precision Optics Manufacturers Association (APOMA) are undertaking a program to modernize the US optics industry, with a focus on introducing CNC fixed-abrasive grinding technology to companies that have relied on traditional multi-part blocks and loose-abrasive grinding[1]. One of our goals in collaborating with COM is to better harness advanced sensors and control strategies for improving process economics and workpiece quality for this new generation of precision CNC optics grinders.

For CNC spherical generation, grinding cycle time is dominated by the accumulation of in-feed times. For a single operation, the in-feed can be divided into five steps: 1) fast approach, 2) approach leading to contact, 3) grinding, 4) dwell (zero), and 5) fast retraction. The grinding operation usually accounts for the longest duration of in-feed (about 1 minute). However, for medium and fine grinding, the time required for the approach to contact (2) may be about the same duration as for grinding, depending on the methodology. If the rate of in-feed during this phase of 'finding the part' is low, then productivity is reduced by what has been dubbed 'air grinding'.[2]

A reliable proximity sensor, coupled with feedrate over-ride control for the machine tool, could greatly reduce the time to 'find the part'. One approach is to use a force sensor and detect proximity by sensing the increase in force due to tool-to-workpiece contact.[2] Alternatively, acoustic emission may be used in the same mode of contact detection and for monitoring the 'spark-in' process.[3] In fact, Table 1 lists a number of commercial sources of AE systems for detecting tool-to-workpiece contact.

In this paper, we consider the use of AE sensors for determining the proximity of the grinding wheel to the workpiece *prior to the initial contact with the workpiece.* We feel this is an appropriate strategy for the fine and medium grinding of glass optical surfaces and other brittle materials, where excessive subsurface damage might be created by initial high-speed contact.

Approach

We conduct our grinding development on a T-base diamond turning lathe that has been converted to a spherical generator. Glass workpieces are cemented to holders held in a collet in the

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10-inch air bearing part spindle mounted on the z-axis. Bound-diamond cup wheels are mounted in collet-taper adapters for the high-speed air bearing tool spindle located on a rotary table on the x-axis. The machine tool has laser interferometer position feedback with 1 µinch resolution. The nominal operating conditions for many of our tests are given in Table 2.

During testing, we cement an AE sensor to the back of a workpiece, with the leads extending back through the part holder, to a pre-amplifier mounted inside a cavity in the spindle. The basic set-up of our equipment is shown in Fig. 1. The signal and power lines from the pre-amplifier extend through the back of the spindle to a set of slip rings. Either within the pre-amplifier or as an auxiliary stage, we typically use a band-pass filter to eliminate aliasing (e.g. 1.2 MHz) and to minimize low frequency variations. The signals are typically viewed on an oscilloscope, and then are sent to a personal computer (Apple Macintosh) using a data acquisition package (National Instruments Labview). Once collected within the computer, we perform various mathematical calculations, including RMS power, filtering, and power spectral density (Matlab from the Mathworks). As indicated in the figure, the amplified signal is also sent to an envelope detector, which rectifies and filters the signal, producing a relatively-smooth positive signal that is proportional to AE signal power.[4]

Our testing procedure generally involves measuring AE signals with respect to a defined position of 'contact' between the wheel and the workpiece. Our approach to defining the contact position is to perform a grinding operation followed by a long-term dwell period (> 1 minute). At this point, we assume that material removal is essentially complete, and that most of the elastic deflection of the machine structure has relaxed (via material removal). We define this condition of long-term dwell as the zero-separation condition. Clearly, this is an imperfect definition, because of the uncertainties

Table 1. Vendors of AE Proximity Systems.

Euchner-USA Inc. Hibernia, NJ TEL: (201) 586-2600	Gap Eliminator
Montronix Ann Arbor, MI TEL: (313) 677-7890	TS100
Physical Acoustics Corp. Princeton, NJ TEL: (609) 896-2255	Tool Touch Detection System
Promess Inc. Brighton, MI TEL: (810) 229-9334	Drill Monitoring System using AE
Prometec Inc. Ann Arbor, MI 48108 TEL: (313) 998-0001	Process Monitor: G90, G100, G110, G200

Table 2. Nominal operating conditions

Grinding wheels	Diameter: 52 mm Concentration: 75 Medium: 10-20 µm Fine: 2-4 µm
Tool spindle speed	15000 RPM
Work spindle speed	180 RPM
Grinding in-feed rate	Medium: 50 µm/min Fine: 7 µm/min
Total grinding in-feed	Medium: 50 µm Fine: 12 µm
Workmaterial	BK7, 40 mm dia. 50 mm thick
Coolant	Challenge 300HT 12.5 gpm; 20 ± 0.2°C

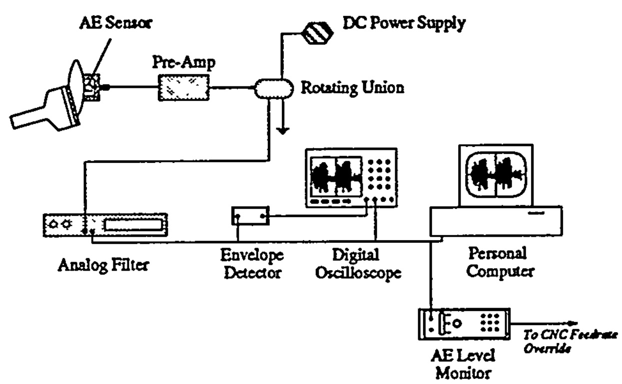

Figure 1. Experimental set-up for AE acquisition.

regarding residual machine deflection, but we believe that it is a suitable reference point for these experiments. There may remain a level of elastic interaction between the tool and the workpiece, leading to a continuing AE signal.[5]

Results

In Fig. 2 is shown a sequence of AE signals measured for different tool-to-work separations, for a single grinding operation. All of the scale lengths are identical for inter-comparison. The length of the abscissa is 6 milliseconds and corresponds to approximately 1.5 revolutions of the tool spindle. Separation is determined by the cumulative z-carriage moves that occurred after a long-term dwell following an earlier grinding operation.

In Fig. 2a is shown two low level signals obtained for large tool-to-workpiece separations. The tool is about 1 mm away from the workpiece in the lower plot and effectively represents the background signal level. The upper plot in (a) shows that the signal increases as the separation closes to 3 microns; we attribute this increase in signal level to turbulent interactions among the tool, the coolant, and the workpiece. In Fig. 2b, the separation is decreased to 1.5 microns, and the rms signal level exhibits a modest increase. As the separation is decreased to 0.5 microns in Fig 2c, AE signal bursts are observed, corresponding to the 'once-per-rev.' period of the tool spindle. In Fig. 2d, as the tool returns to the 'zero' location, determined by the previous dwell operation, the magnitude and duration of these once-per-rev bursts increase. Fig. 2e was obtained during a medium grinding operation with an in-feed of 50 µm/min. Note that substantial signals are observed during the full rotational period of the grinding wheel. Finally, the trace in Fig. 2f shows the long-term dwell (1 minute) of the tool immediately after the grinding operation, which is quite similar to Fig. 2d.

We recorded the sequence of signals from the envelope detector for several experiments similar to that described for Fig. 2, which is shown in Fig. 3a plotted against separation. All of the

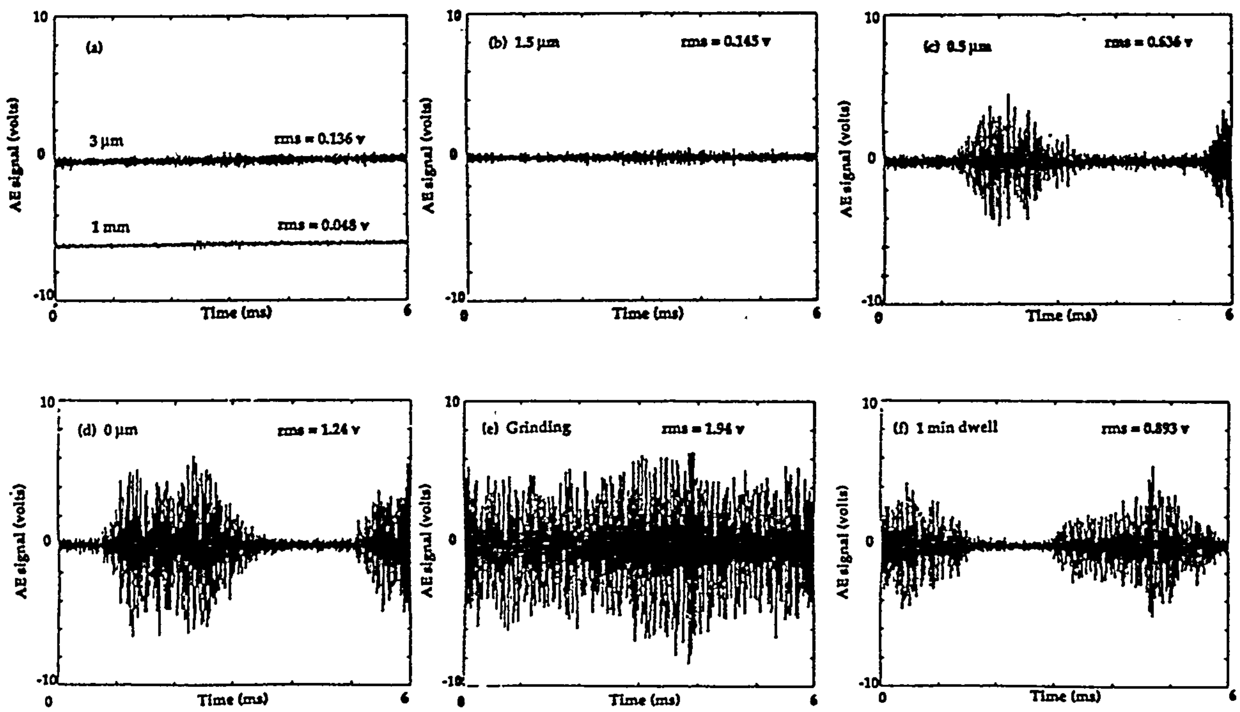

Figure 2. AE signals recorded for different tool-to-workpiece separations and during grinding.

curves measured show a monotonic increase in signal as the separation decreases. Clearly indicated on this plot are the different slope regions corresponding to the turbulent and 'once-per-rev' regions. The turbulent region appears to be identifiable for separations greater than 10 μm. We are also analyzing the source of non-repeatability exhibited in the region labeled as 'once-per-rev'.

In Fig. 3b, we show a potential scheme for using AE information in transitioning from a fast in-feed to a slow in-feed prior to contacting the part. A signal threshold identified in the turbulent regime would trigger the CNC to execute a deceleration routine (shown here as a ramp). A secondary threshold might be invoked in the once-per-rev regime for initiating a faster level of deceleration (shown here as a step). We are currently establishing a feedrate over-ride system on our grinding platform and are assessing the bandwidth and transfer function limitations/requirements for achieving this for various rates of fast in-feed and tool-to-workpiece separations.

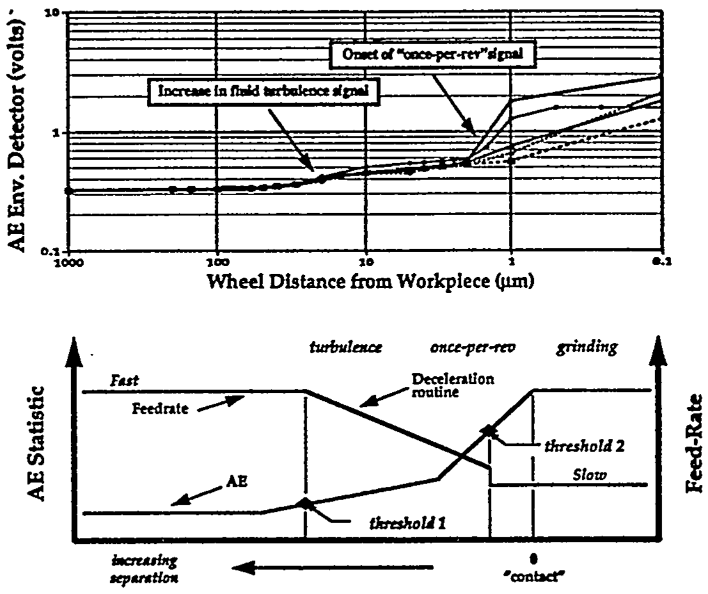

Figure 3. a) AE signal vs. tool-to-workpiece separation; b) schematic illustrating the use of AE for feedrate over-ride.

Continuing Work

Our immediate goal is to evaluate the use of AE as a feedrate over-ride signal in transitioning from a fast in-feed to the final in-feed. We will also perform similar experiments on the grinding platforms at COM. We will work with optics companies to identify specific requirements for in-feed rates and assess the bandwidths of various controller schemes. We are working to identify optimal statistics for use as control variables, although rms power and envelope signal appear relatively robust. Initial discussions with Prof. Ken Beck at CREOL are leading to further strategies for improving the signal-to-noise ratio of the measurements.

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[4] The use of envelope detection is also discussed by 1) reference 3; and 2) Wakuda, M. and Inasaki, I., "Detection of malfunctions in grinding processes", paper presented at the 4th World Meeting on Acoustic Emission and 1st Int'l Conf. on Acoustic Emission in Manufacturing, Boston, September, 1991, ASNT.

[5] de Oliveira, J. F. G., Dornfeld, D. A., Winter, B., "Dimensional characterization of grinding wheel surface through acoustic emission," **Annals of the CIRP**, vol. 43(1), 291-294 (1994).

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