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Implementation of an Acoustic Emission Proximity Detector for Use in Generating Glass Optics[*]

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Background and Motivation

The use acoustic emission (AE) sensing as a method to monitor proximity between a grinding wheel and a brittle material workpiece is being developed at Lawrence Livermore National Laboratory (LLNL) and the Center for Optics Manufacturing (COM) in Rochester, NY[1]. Significantly reducing the amount of expensive 'air-grinding' is one of the primary motivations behind this effort, along with lessening the chances of a crash which could damage the wheel, part and machine tool. AE sensing is well developed and routinely used in the metal working industry[2] for 'initial contact' sensing or tool breakage, for example, and in monitoring diamond turning and grinding processes[3]. However, using AE sensing to switch from a rapid to a final in-feed rate at the detection of initial-contact between the grinding wheel and a *brittle* material workpiece, such as an optical glass, is often unacceptable during fine grinding (less than 10 µm grit wheels) which produce surfaces with roughness values of 100 Å rms or less. In the approach taken here, we are sensing the AE *prior* to contact between the workpiece and the tool. The coolant between the workpiece and the grinding wheel is used as an AE medium to transfer AE signals generated by the relative motions of the coolant, workpiece and wheel. Capitalizing on the repeatability of the AE approach signal, we have developed a system to detect the proximity of the grinding wheel relative to the workpiece prior to initial contact.

Acoustic Emission System Design at LLNL

We have developed and installed an AE closed-loop feedback system on a spherical optics generator at LLNL. Two air bearing spindles are used on the grinder, one for the grinding wheel and the other for the glass workpiece. A through hole in the part spindle accommodates the AE sensor, AE transmission rod and preamplifier as shown in Figure 1. The transmission rod is a lightly spring-loaded, aluminum rod which is acoustically insulated from the machine tool to minimize machine induced noise in the AE signal. By lightly touching the back side of the workpiece, the transmission rod provides a practical method of coupling the AE sensor to the workpiece, thereby ensuring a desirable signal-to-noise ratio. A rotating union provides the means of connecting the amplified AE signal and preamp power lines between the rotating AE components within the grinding spindle and the outside stationary equipment.

Once the AE signal is transmitted through the rotating union, it is low-pass filtered, passed through an rms converting circuit, into a data acquisition system and finally to the CNC to provide the closed-loop feedback signal. The CNC can then utilize the feedback AE information to perform a variety of commands such as reducing the in-feed rate, changing spindle speeds, etc. Figure 2 is a schematic showing a possible scenario in which two AE thresholds are used to initiate CNC responses. In this scenario, the first threshold would trigger a routine with a set commanded lag time allowing a specified continuation of the fast in-feed (lag time) followed by a ramp down in the in-feed rate. This occurs in the *turbulence region* where the wheel is still not contacting the part and the AE is generated with and

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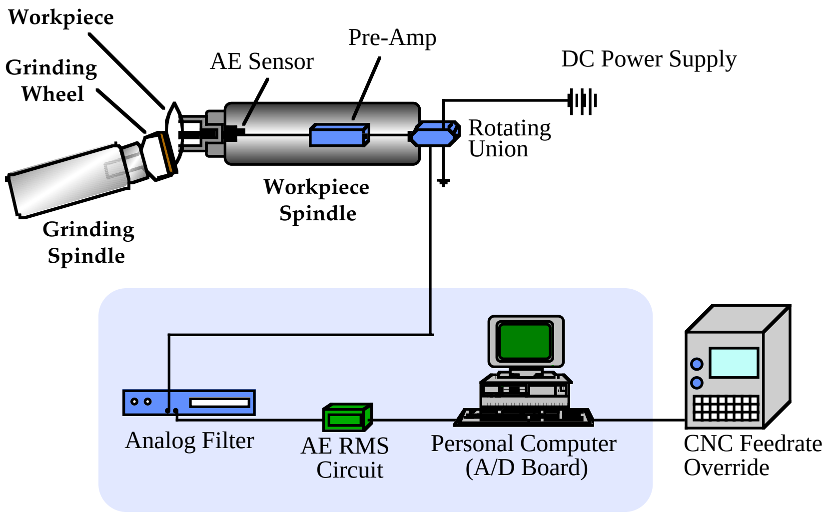


Figure 1. Schematic showing the AE closed loop system at LLNL.

transferred through the coolant layer between the wheel and the part. The next region is referred to as the *once-per-revolution region* in which the wheel is just beginning to make contact with the part due to axial error motions occurring every one revolution of the wheel. This region is noted by a sharp increase in the AE level and the second threshold located in this region could then be used to trigger a quick-change in the feed rate down to the final in-feed rate for the fine grit wheel. And lastly, the final region, *grinding*, is characterized by high, relatively constant AE levels. Repeatability of the AE approach signal is the key which allows exploitation of this process for use as a wheel-to-workpiece proximity sensor.

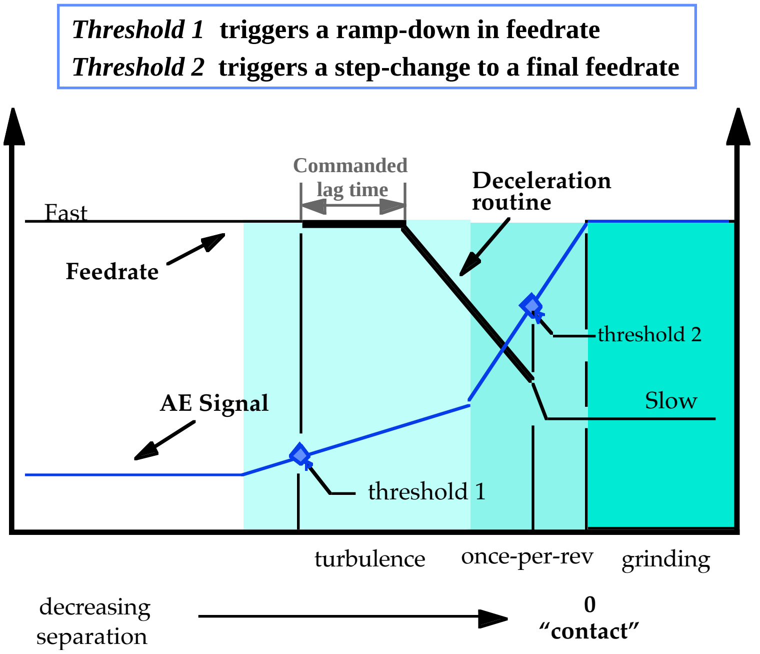
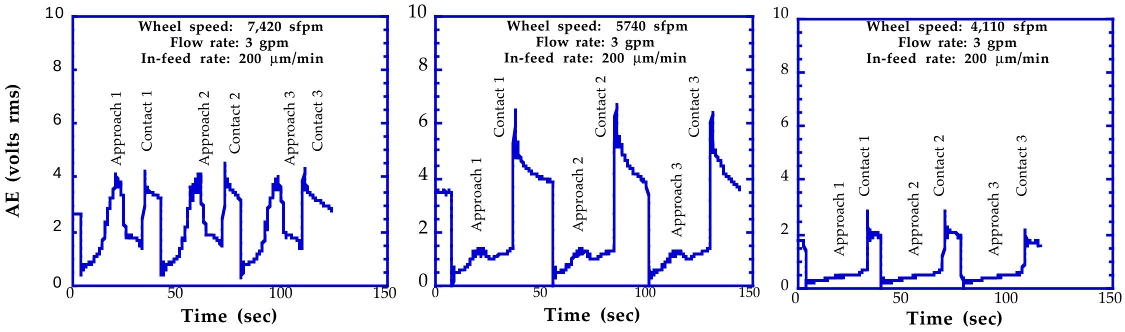


Figure 2. Using two distinct AE level thresholds is a possible implementation method of a closed-loop AE feedback system.

Acoustic Emission Data from LLNL's System

As might be expected with a system like this, it is sensitive to a number of operating parameters such as wheel speed, wheel configuration, coolant flow rate and approach angle of the grinding wheel. For example, Figures 3 a-c, show approach AE data for three grinding situations where the only process parameter change was wheel speed. The data acquisition process began with the approach of the grinding wheel toward the workpiece. Some approach data, such as Figure 3a will have a distinct ridge where the AE signal increases to a certain point and then decreases as the wheel gets closer to contacting the part. Other data will monotonically increase as the wheel-to-workpiece separation decreases, like Figure 3c. From left to right, Figures 3 a-c show approach data for three cases where the wheel speed is decreased. Focusing on only the approach portions of the data, it is evident that the AE levels during the approaches decrease with wheel speed until, in Figure 3c, the signal is almost unusable. The different AE magnitudes of the *contact* points is attributed to thermal growths of the wheel, workpiece and fixturing where a fraction of a micrometer may result in a significant change in the once-per-rev signal, where little material removal takes place. Although these signals may vary as process parameters are changed, when they are held constant, as they typically are during grinding, the AE approach signals are quite repeatable. It is this repeatability of the AE approach signal that allows sensing of the AE signals to be used as a proximity detector. Overcoming different AE approach characteristics as parameters are modified can be accomplished through a quick CNC calibration routine (i.e., recalibrate the system if parameters are changed).



(a) **(b)** **(c)**

Figure 3. Approach AE signals for three different wheel speeds.

Since the repeatability of the AE system depends on the AE level threshold monitoring, tests were generally conducted using three different in-feed rates, from 50 to 200 µm/min. Figures 4 a and b, show repeatability data for two identical grinding conditions, but with two bronze bond, 2/4 µm diamond wheels with different body configurations. The tests consisted of initially grinding and dwelling on the part to establish the zero point. The wheel is then commanded off the part 100 µm, fed in towards the part until an AE threshold is reached. The CNC then commands the in-feed to stop and the separation distance is recorded.[*] This process is repeated 20 times to measure repeatability. Adjusting the threshold level will affect the separation stopping distance and can be dialed-in for a desired separation distance.

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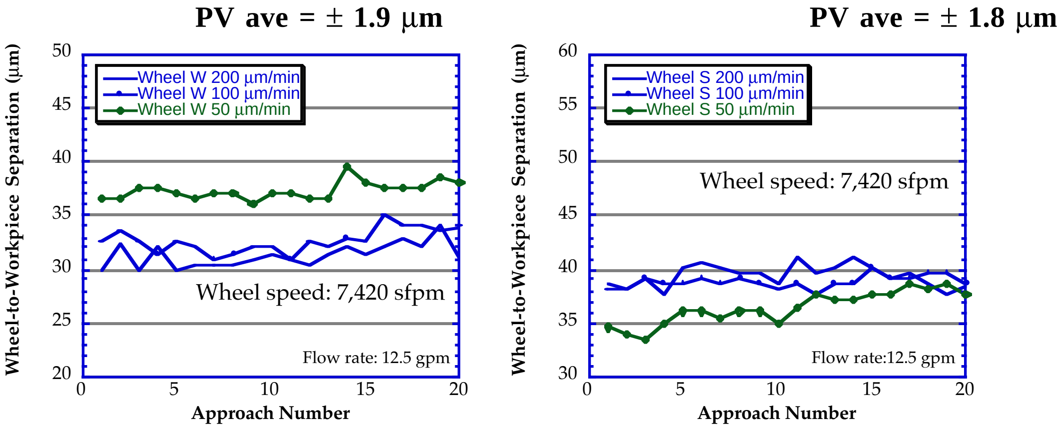
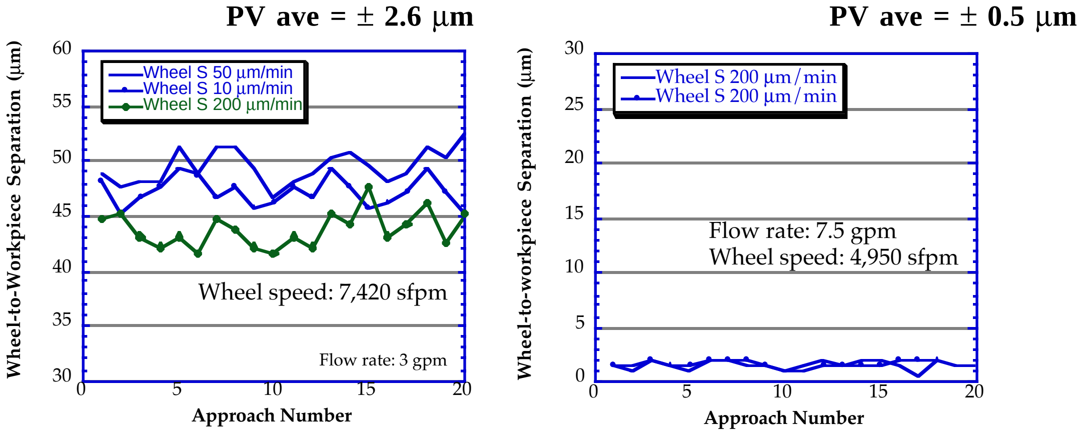
[*] Note that this separation is 'implied' from the axis position of the machine tool. Actual separation is sensitive to grinding zone thermal fluctuations which are not reflected in the axis position. This is one source of non-repeatability error in the test data.



(a) **(b)**

Figure 4. Repeatability data for two different body configurations of wheels.

Figures 5 a and b show repeatability data for two more grinding scenarios. Figure 5a uses the same parameter settings as in Figure 4b, except that the flow rate is reduced from 12.5 gpm to 3 gpm. The result was a more noisy signal which resulted in a greater PV variance. Figure 5b presents two identical repeatability runs, but in this case the wheel speed was 4950 sfpm and the flow rate was 7.5 gpm. This produced a relatively low AE approach level that resulted in a close stopping distance from the part (1 to 2 µm separation). The peak-to-valley variance of this case was by far the lowest of all the cases that corresponded to the approach signal also being the least noisy. The repeatability data for these cases is also a function of sampling strategy (filtering, rms calculation, time averaging) and balancing optimum repeatability and minimum response time is required for each grinding situation.



(a) **(b)**

Figure 5. Repeatability data for two different parameter settings with the same wheel.

An additional benefit to the AE proximity system is that it allows real-time monitoring of the grinding process that can reveal such information as the need for the wheel to be dressed. Figure 6 shows an example of this. The upper left plot is of data acquired during a nominal grinding process. After an initial long term dwell, the wheel backs off the part, feeds in, grinds the part and dwells (sparks out) for 45 seconds. As seen in this first plot, the AE signal drops off quickly in the dwell region. The upper right plot is data from an identical run, but this time the wheel is in a loaded condition and needs to be dressed. Data in this plot contains much more noise and the dwell signals remain at relatively high levels. After dressing the wheel, another run is made and the bottom plot shows the resultant data with the return to nominal AE grinding characteristics.

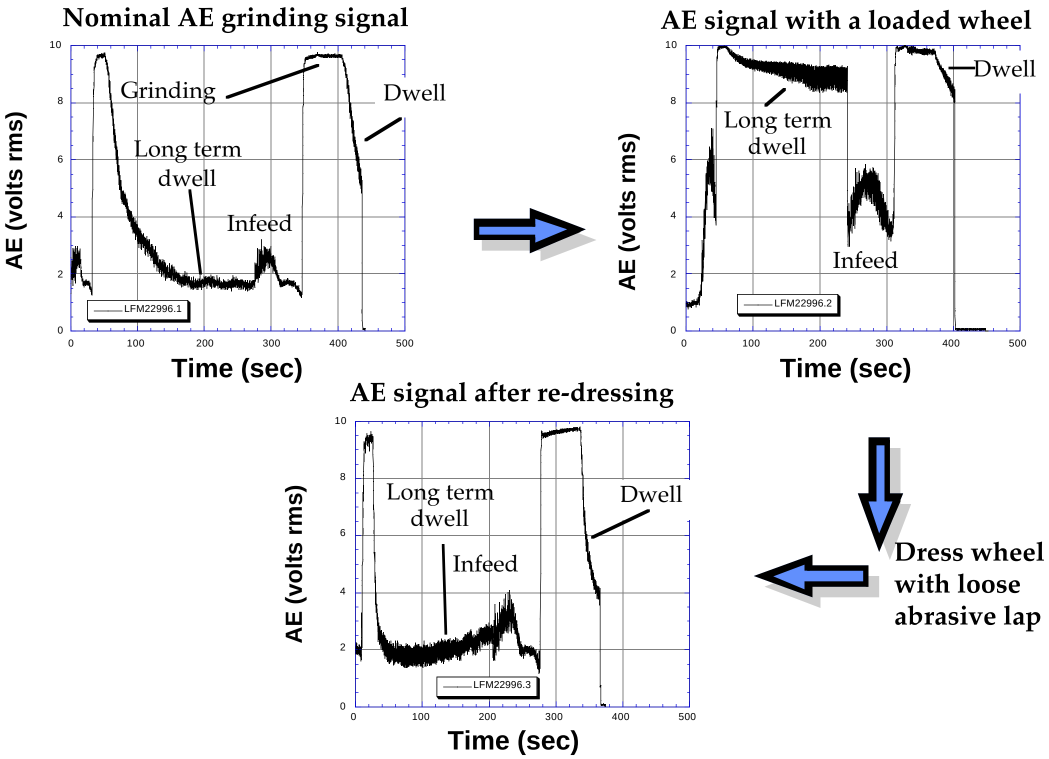


Figure 6. Using AE to monitor in-process grinding data reveals information such as the need to dress a wheel. Bronze bond, 2/4 µm diamond wheel, grinding BK7 glass.

Commercialization

An AE system similar to the one at LLNL is currently in the development and testing stages on commercially available spherical generator, the Micro SX from CNC Systems[4], and is located at the COM. The Micro SX has two vertically mounted spindles and can generate parts up to 25 mm in diameter. A significant difference between the LLNL generator and the Micro SX is that the Micro SX utilizes roller bearing spindles which tend to introduce more AE noise into the system. Sufficiently isolating the transmission rod from the workpiece spindle and filtering of the AE signals provides a useable AE signal.

Figure 7 is a close up view of the workpiece chucking mechanism, the transmission rod assembly and the AE sensor. The AE signal line exits the bottom end of the spindle and is connected to the preamp, which is also rotating with the spindle. The AE sensor is mounted on the lower end of the transmission rod and the sensor cable is fed through a center hole in the belt-driven spindle. The amplified AE signal is routed through a rotary union and is brought out to a data acquisition system and the Micro SX's CNC. Special programming of the CNC's programmable logic controller will provide the AE level threshold monitoring necessary for the closed-loop feedback implementation. Initial tests will be used to measure repeatability and robustness of the AE system as a wheel-to-workpiece proximity detector. An additional feature is that real-time in-process information will be available by monitoring the AE signal during grinding.

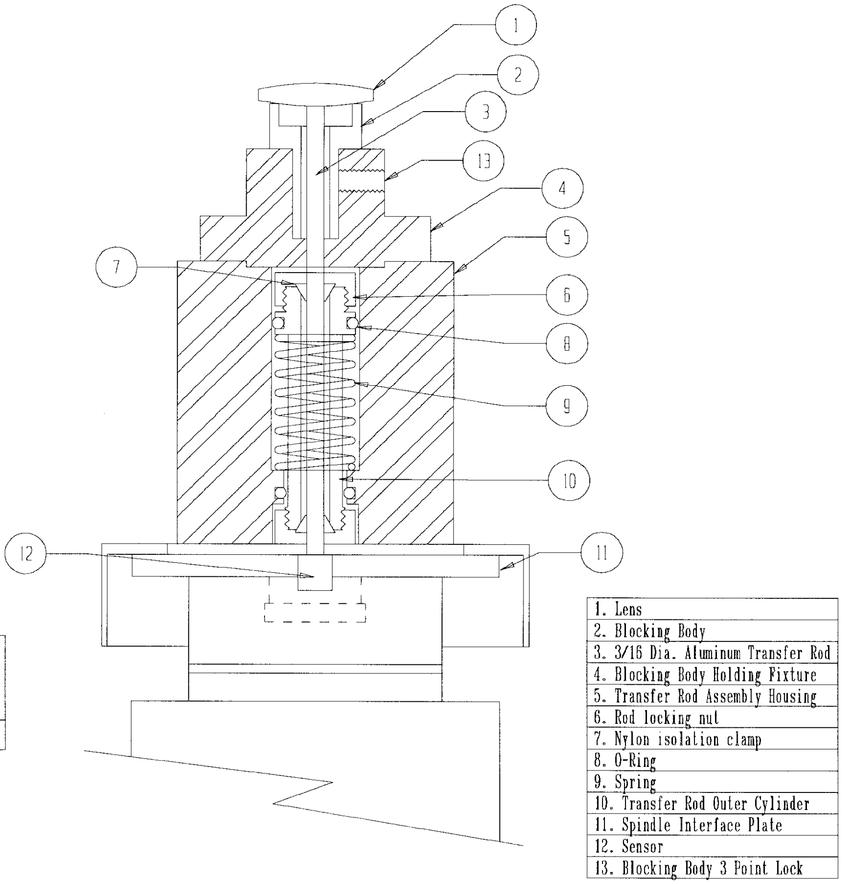


Figure 7. Detail of the acoustic emission sensor fixture for the OptiPro 100.

Summary and Conclusions

We are using the approach AE signal during a grinding operation to detect the proximity of the grinding wheel relative to a brittle material workpiece and are using this detection as a feed-back control signal in our CNC. The repeatability of the AE signal during the wheel approach is the key that allows AE to be used as a proximity detector and is demonstrated at LLNL to be about ±2 µm. We noted significant changes of the AE signal as process parameters are modified, but conclude that with a quick CNC calibration routine and holding the parameters constant during a given operation, the AE system can be successfully used to sense pre-contact wheel-to-workpiece separation. Additionally, the AE sensing system allows real-time monitoring during grinding to provide in-process information. The first prototype of an AE system on a commercially available generator is currently be tested at the Center for Optics Manufacturing.

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[1] Taylor, J.T., Piscotty, M.A., Blaedel, K.L., Dornfeld, D.A., Weaver, L., “Investigation of Acoustic Emission for Use as a Wheel-to-Workpiece Proximity Sensor in Fixed Abrasive Grinding,” ASPE Annual Meeting Proceedings, Volume 12, October, 1995.

[2] Dornfeld, D.A. "Acoustic Emission and metalworking - Survey of Potential and Examples of Applications," 8th NAMRC Conf., May 18-21, 1980, pp 207-213.

[3] Bifano, T.G. and Yi, Y. "Acoustic Emission as an Indicator of Material Removal Regime in Glass Micromachining," Journal of Precision Engineering, Vol. 14, No. 4, October 1992, pp 219-228

[4] CNC Systems, Inc., 369 Route 104, Ontario, NY 14519. Mike Bechtold, President.

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