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Application of AE Contact Sensing in Reliable Grinding Monitoring

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Abstract
The low repeatability of the AE RMS level and its weak correlation with some grinding quantities has been the main problem that limits the use of this sensing technique in industrial environments. This paper presents results on the influence of some measuring conditions on the AE information. Some reliable grinding monitoring functions are proposed for production based on fast RMS analysis and binary contact detection techniques. An innovative grit mapping technique is introduced based on these new concepts. Some examples of application that include information about the topographic characteristics of a grinding wheel and its transformation during grinding are presented.

Keywords: Grinding, Process monitoring, Acoustic emission

1 INTRODUCTION

The application of acoustic emission (AE) in grinding monitoring has been researched since 1984 [1]. One of the first conclusions of this research was the high sensitivity of the AE (root mean square) RMS level in the detection of contact between the grinding wheel and the workpiece. This was confirmed by Inasaki in 1989 [2] and 1991 [3], Blum 1990 [4] and König 1990 [5] and 1993 [6]. The CIRP Tool Condition Monitoring keynote [7] confirms that and presents several features that can be extracted from the AE RMS signal for process monitoring and diagnosis. The contact detection capabilities of AE information were investigated relative to the topographic characteristics of both contacting surfaces in 1994 [8,9].

The use of acoustic emission signal based monitoring systems in industrial grinding is growing in the recent years. However the amount of non functional systems detected 5 years ago [7] is still high even after a considerable amount of research effort.

Figure 1 shows the research and industrial status of some relevant problems for several grinding operations. It also lists the sensors/quantities that can be feasible to be applied for solution. The information shown in figure 1 was based on an extensive literature review and several visits to machine tool manufacturers and grinding users. The two main features that can be observed in the figure are: the number of unsolved industrial grinding problems and the potential use of AE to help in their solution. Most of the AE monitoring systems available in the market use a dynamic or static threshold to compare with the instantly calculated AE RMS value for a chosen filtering and gain setup.

However, several factors may influence the AE RMS level in a non predictable way. They include disturbances from minor changes in: sensor positioning, coolant flow, machine noise, electrical noise and grinding wheel topography. To solve this problem, some research has been conducted towards new signal processing techniques or multi sensor analysis. But even with these new proposals, most industrial applications are still restricted to contact detection between grinding wheel and workpiece or dressing tool.

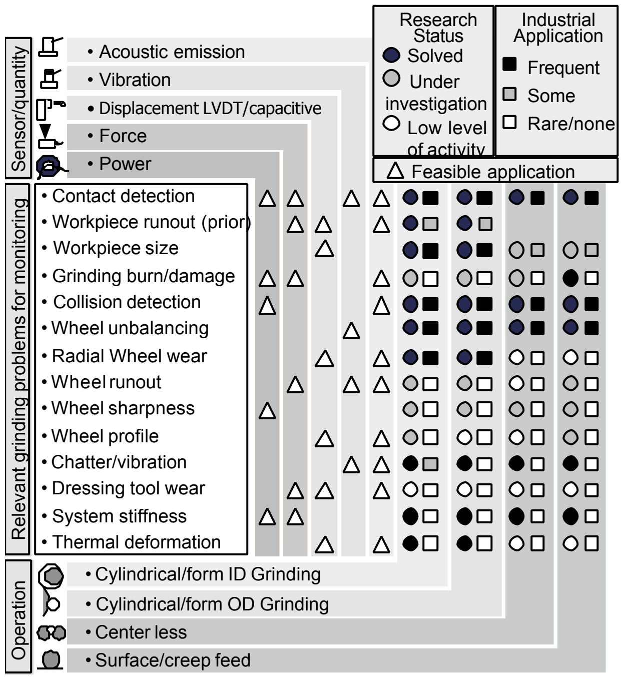

Figure 1 – Relevant Grinding Problems for Monitoring.

One of the interesting features of the AE instability is its time dependence. Normally in laboratory tests AE RMS shows very good correlation with other grinding quantities in shorter periods of time. This happens because bearing noise or machine deformations take a considerable time to change relative to the cutting event in grinding. There is a requirement for a more reliable strategy so that frequent recalibration is not needed (thus preventing users from simply switching off the system when it goes out of calibration). This paper presents data on some strong sources of disturbance that may affect the AE information and proposes a number of more reliable strategies for AE monitoring in industry that will insure a more successful application.

2 AE LIMITATIONS

The main limitations of the AE RMS analysis are unpredictable changes in signal linearity and amplitude with time. The linearity between the AE and the dressing or grinding quantities can be caused by signal saturation in the 1st stage of the preamplifiers. In the dressing operation, when the sensor is positioned close to the diamond dressing tool, the sensor output can reach values higher than the power supply voltage. This leads to a partial clipping of the raw information that is hard to observe in the RMS output. Figure 2 shows the result of an experiment where a dressing operation was performed for five depth of cut values, two sensor positions and two gain levels in the input amplifier (high=60dB and low=40dB). The set-up with high input amplifier gain (the first stage preamplifier) had a low RMS amplification. The sensor position (labeled "near" in the figure) was in the dressing tool holder and the other position (labeled "far") was in the machine slide. Between the slide and the dressing tool holder were 2 mechanical interfaces. The relationship between dressing depth of cut and AE RMS level shows 3 different behavior:

1. Linear: when the sensor is far from the dressing tool. The sensor output has a low clipping level.
2. Logarithmic: when the sensor is near the dressing tool and the input gain is low. Higher clipping level.
3. Quasi constant: when the sensor is near the dressing tool and the input gain is high. High saturation.

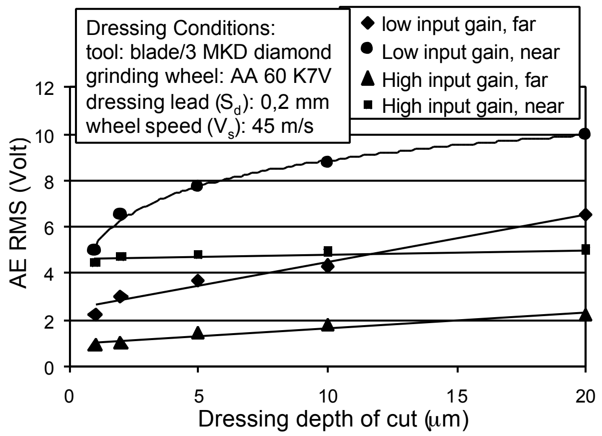

Figure 2: Correlation between AE RMS level and dressing Depth of cut for 2 input gain and sensor position.

It is interesting to note that even with a high clipping level in the first amplification stage, as the output level was set relatively low and the signal had some dynamics, it did not appear to be saturated.

This example shows how the use of a dynamic threshold for dressing can fail since an expected correlation between AE RMS and dressing depth of cut does not occur.

Another source of trouble in AE monitoring is the RMS level instability. The AE level may fluctuate up to 50% of its value after some hours. One of the main reasons for this signal oscillation is the variable performance of the machine interfaces in transmitting the AE signal. Figure 3 shows the results of two dressing experiments made with the same condition shown in figure 2 with the sensor far from the dressing tool and with low input gain. One experiment was done during the machine warm-up and the other one after about one hour. As can be observed from the plotted linear regression the average sensitivity during the warm-up was higher but with a high dispersion. After warm-up the AE sensitivity to the dressing depth of the cut was lower, but with less dispersion. The test had a random sequence for each case.

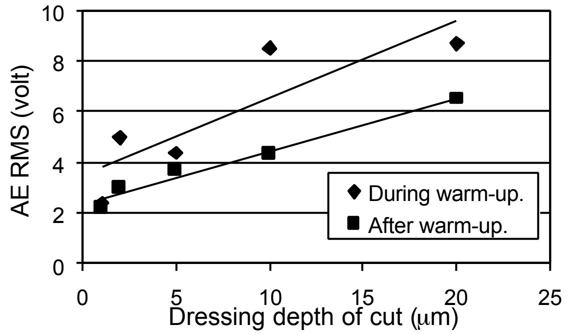

Figure 3: Correlation between AE RMS level and dressing Depth of cut for 2 different experiments.

The explanation for the high dispersion during the warm-up is due to the high variation in the effective contact area in the interfaces when the machine responds to thermal deformation. Since the sequence of tests was random, the variation with time (which is not linear) produces a scattered distribution along the linear regression line.

These influences make the conventional AE RMS solutions difficult to apply in production lines leading to frequent need of human interference for adjustments. Other quantities that may intensely influence the AE RMS in an unpredictable way in dressing and grinding are: number of diamonds in contact (for multi point dresser), coolant pressure, workpiece microstructure or hardness variation, grinding wheel wear (within acceptable range may lead to large AE variation), wheel hardness grade, etc. These influences have been experienced by the authors in practice in industrial environments, but the relative influence are still unknown.

3 RELIABLE AE APLICATION

As presented above, the two main limitations of the AE monitoring solutions are the oscillation of its RMS level and its saturation. However AE can be very effective and fast for the contact detection of moving surfaces. This characteristic can be better explored in two different ways as following.

3.1 Fast AE RMS analysis

This method is based on short analysis of AE RMS patterns. Since AE RMS changes occur after a considerable period of time, the short time evaluation could be a solution for a reliable AE application. Figure 4 shows the proposed system where the acoustic emission obtained from the contact between diamond tool and grinding wheel (or grinding wheel and workpiece in grinding monitoring) is converted to RMS level and acquired by the computer by using an analog to digital conversion board. The sampling rate range varies from 60,000 to 500,000 samples per second, depending on the chosen resolution in the circumferential direction.

To be able to detect the contact of the diamond tool with each abrasive grain, the RMS calculation must be done using a very short time constant. The time constant was calculated as the average time spent for two consecutive hits between abrasive grains and the diamond tool. This calculation was done for a 60 mesh, L structure Aluminum Oxide wheel. The average distance between grains measured was about 0,38mm. The grinding speed was 45m/s, so a very fast time constant of 20 microseconds was found.

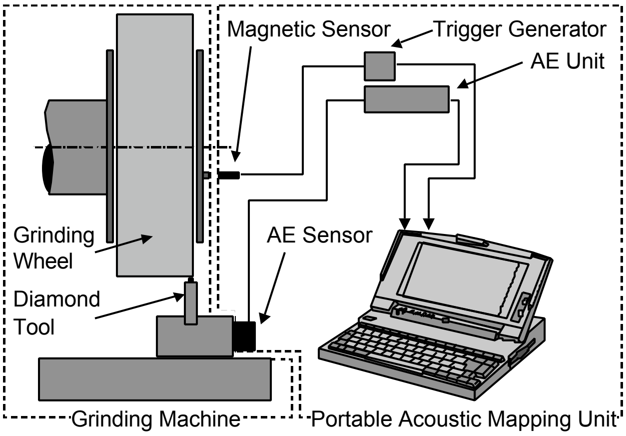

Figure 4: Setup for the fast RMS Analysis based mapping.

Due to the very small time constant chosen in the RMS circuitry, a high pass filter with a cut-off frequency of 100kHz was established. A specific AE signal processing unit has been developed for this system.

The data acquisition is made in data arrays corresponding to a full rotation of the grinding wheel and is triggered by a sensor positioned on the spindle. The number of samples of each data set is calculated based on the chosen resolution:

$$NS_r = (D_s . \pi)./R_{es} \quad (1)$$

Where: D_s= Grinding Wheel Diameter (mm),

R_{es}= System Resolution (mm),

NS_r = Number of Samples per Rotation.

The sampling rate is calculated based on grinding speed (v_S) and number of samples per rotation of the grinding wheel:

$$S_r = (v_s . NS_r)/(D_s . \pi .) \quad (2)$$

Where v_s = Wheel peripheral speed (m/s),

S_r = Sampling rate (Kilo samples/s).

The image is built up by representing the AE level of each acquired sample with a color scale in a 3 dimensional graph. In this paper a gray scale was used. During the dressing operation the image is constructed in real time by adding columns in the array as the dresser travels along the wheel surface. Figure 5 shows this procedure.

The system can be used in 3 different ways:

- Dressing evaluation: During the dressing operation the interaction between dresser and grinding wheel can be acoustically mapped. Lack of contact between dressing tool and grinding wheel will appear as dark areas in the map.
- Topographic mapping: In this case the map is similar to that obtained for the dressing operation but using the dressing depth of cut nearly zero or with a value close to the undeformed chip thickness for the operation. In this case the map shows the active surface of the grinding wheel, which means the surface that will actually be in contact with the workpiece during grinding.
- Grinding evaluation: During a plunge grinding operation the interaction between the grinding wheel and the workpiece can be evaluated. In this case a different map is obtained where one axis is the grinding time and the other shows the average acoustic energy in the whole wheel length along its circumference.

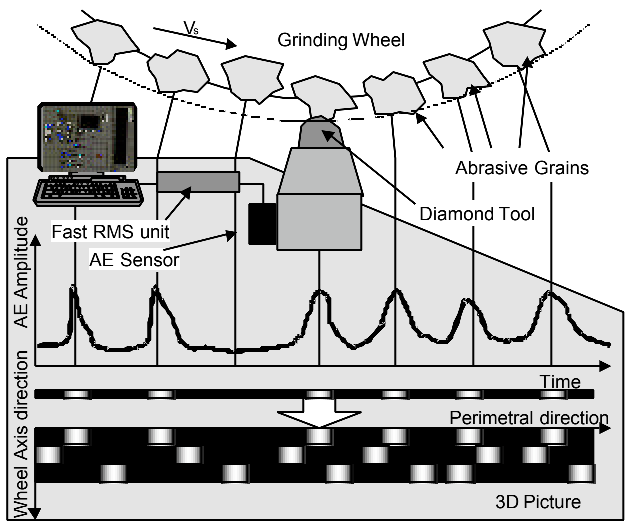

Figure 5: Image construction procedure for fast RMS analysis.

Figure 6 shows an output from the acoustic mapping system when used during a dressing operation. The vertical and horizontal directions are the wheel circumference and width respectively. The resolution is of 2 samples/mm. The depth of interaction between diamond tool and grinding wheel used was 1 micron (in the range of elastic contact [1]). The gray intensity shows the acoustic emission RMS value measured from the interaction between dressing tool and the abrasive grains. Darker areas means less acoustic energy detected by the sensor. The L shaped mark was created in the wheel surface in order to check the system functionality. The darker band on the left side was caused by a grinding operation using that area of the wheel.

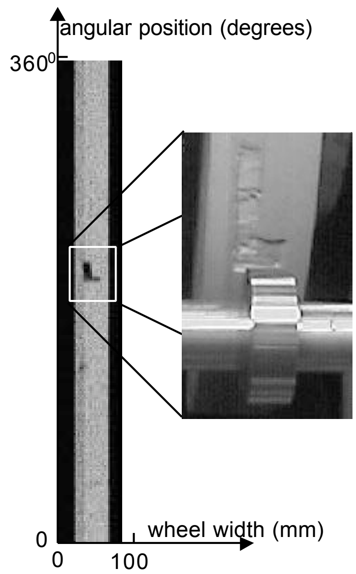

Figure 6: Output from the acoustic mapping system.

Figure 7 shows the map obtained from grinding operations in two different conditions. In a grinding operation the map shows how the acoustic energy is distributed around the wheel surface with time. So, now a different map is presented. The vertical direction shows the average AE RMS level for the whole grinding wheel width and the horizontal direction shows the grinding time. Each stripe in the graph represents a single grinding cycle or a single workpiece. The first set of data was collected in a production line of engine components. The workpiece material is Inconel and the grinding wheel is a very hard grade, low friability aluminum oxide specification (DA 80 R V).

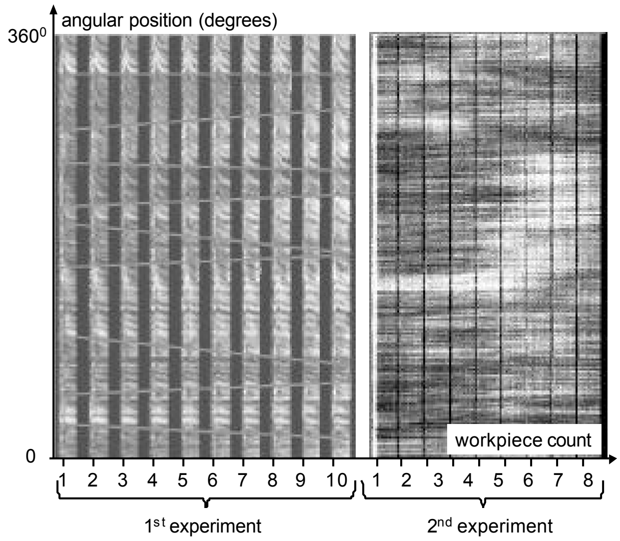

Figure 7: Output from the acoustic mapping system during grinding in two different conditions.

The second experiment is plunge grinding of a hardened AISI 4340 steel using a soft white aluminum oxide grinding wheel (AA 60 G V). The image composition of the several pieces shows 2 different types of wheel wear behavior. In the first experiment the maintained pattern around the wheel shows that it is not loosing grains. In the second experiment the transformation indicates that the wheel is loosing grains. These results were confirmed by checking the workpiece size plot (stable for the first case and an increasing tendency in the second case), workpiece temperature (grows for the first experiment and constant for the second) and power plots (power grows in the 1st experiment and remains constant for the second one).

Since the main feature used to evaluate the process is the obtained graphical pattern this system is not influenced by the RMS fluctuation along the time. The fluctuation would lead to changes in the image intensity or contrast of a given pattern. Therefore the diagnosis based on the obtained pattern would not be influenced by temperature or other long term AE disturbances.

The graphical analysis of the obtained pattern could be directly related to some anomalies in the grinding process. Some other test results include:

- Unbalanced wheel: The pattern shows a horizontal dark band as a result of the low wheel interaction in lower mass angular position.
- Grinding Chatter: Shows horizontal patterns when the grinding wheel gets wavy. Shows inclined patterns when there is no synchronization between wheel and the vibration phenomena.
- Regulating wheel eccentricity (for center-less grinders): The obtained pattern shows several vertical dark bands representing lack of contact between wheel and workpiece. The distance between bands corresponds to one revolution of the regulating wheel.

This is a powerful technique to be used in several other applications in grinding. It is reliable since the RMS level is not the main feature but the pattern obtained around the grinding wheel is the basis for monitoring.

3.2 Binary AE detection

The binary detection is a very simple strategy. Since the unstable RMS behavior and the unpredictable linearity between AE and the grinding quantities are the main problems, the binary detection uses a very low threshold and a high gain combined with a fast RMS in order to precisely detect contact. From the precise contact detection between wheel and workpiece or wheel and diamond dressing tool, several other applications can be developed. This method is reliable since the low threshold combined with the high gain doesn't require frequent adjustments in the monitoring unit. This is due to the fact that the threshold value is not relevant when compared with the saturated RMS value. The main applications of the binary approach are: grinding wheel automatic preset (measuring the wheel with a diamond probe), workpiece dimensional measurement before grinding (to monitor the previous machine operation), anti-collision systems, sparkout control and touch dressing contact detection Fast RMS time constants are required in order to get a precise and fast response.

4 CONCLUSIONS

The main conclusions that can be drawn from this research are:

- The use AE RMS dynamic and static threshold monitoring strategies may result in low reliability due to the unpredictable behavior of the AE RMS level.
- The proposed mapping system is an innovative approach to aggregate information about the grinding wheel and its action during the grinding process.
- The acoustic mapping system is able to give information about the grinding wheel topography, the dressing operation and the interaction between the grinding wheel and workpiece during a grinding operation.
- The binary detection strategy can reliably monitor the grinding events such as contact, spark out, and dressing in the presence of process disturbances.

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