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WORKPIECE BURN DETECTION DURING GRINDING BY ACOUSTIC EMISSION

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Abstract: A fundamental difficulty in controlling grinding damage is the lack of a reliable method of providing in-process feedback during grinding. In grinding of metals, the damage is referred to as workpiece burn. In this work, the acoustic emission signal is acquired for two different steels, the 52100 bearing steel (soft) and the inconel (relatively hard). This work is distinguished by a high sampling rate (2.56 MHz) data acquisition system and the signal processing of the raw signal instead of the RMS, often used for this purpose. The investigations have shown signs of burn in the frequency domain, in the time domain, and in the correlation between wheel rotations.

Keywords: Acoustic Emission, Grinding Process, Monitoring, Burn

1. INTRODUCTION

The application of AE to monitoring of grinding and machining is not new, and a number of excellent papers have been written on the subject; we list some of these (Bennett, 1994, Berkovits et al., 1995, Chang et al., 1993, Dornfeld, 1994, Konig et al, 1990, Akbari et al., 1995). For the most part these researchers have relied on AE power (sometimes called root-mean square, or RMS, AE) and statistics derived therefrom to determine grinding condition and performance. What distinguishes our work from the previous is the use of a high-frequency (2.56 MHz) analog to digital converter (ADC) coupled with massive data storage, and the consequent availability of essentially raw AE signals. This paper deals with the analysis of data records relating to thirteen grinding runs, involving two different materials. In each case AE data was sampled for the entire grinding pass and analyzed off-line, with results compared to inspection of each workpiece for burn and other metallurgical anomaly. A number of statistical signal processing tools have been evaluated, and an emphasis has been placed on those which are em amplitude-independent; that is, features which are unaffected by overall AE power. This is due to the fact that AE power can rise and fall during a grinding process for reasons having less to do with the workpiece condition than with geometry. Unfortunately, most of these amplitude-independent indicators have failed to recognize burn. A notable exception is a novel statistic which, in the absence of an accepted term, we shall refer to as em wheel-period correlation. It turns out that AE data arising from one revolution of the grinding wheel correlates surprisingly closely with succeeding revolutions. Interestingly, this phenomenon can be employed to determine highly accurately the grinding wheel rotational speed; and further, it appears that variation in wheel speed can indicate burn. More important, we have found evidence that the strength of the correlation is also predictive of burn.

2. EXPERIMENTAL PROCEDURES

The experimental set-up is shown in figure 1, carried out on the Edgetek Superabrasive Machine. Specifically, data from thirteen different experiments involving two different workpiece types were collected, one of these being a relatively difficult-to-grind metal (inconel 718), and the other an easy-to-grind bearing steel (52100). Most parameters were kept constant among all tests; however, the depth of cut, ranging from very light to aggressive, was varied. All workpieces were examined post-mortem, and signs of burn or other stress noted.
Grinding parameters include:

- Nominal wheel peripheral speed: 75.8 m/s (approximately 7500 rpm)
- Nominal workpiece feed rate: 12.7 mm/s
- Coolant type: Master Chemical VHP 200
- Coolant flow rate: 29 gallon per minute
- Grinding wheel type: WOLFCO, CBN 1012, 100/120-CBN, M.O.S. 6115
- Grinding wheel diameter: 7.5 inches
- Grinding apparatus:

Data was retrieved from a single Physical Acoustics PAC U80D-87 sensor, mounted directly on the work table of the grinding machine via adhesive. The data acquisition system employed was a HP E1430A run in continuous-sampling mode at 2.56×10^6 samples per second. The A/D accuracy was 16 bits per sample, and appropriate anti-aliasing filtering was performed internally to the HP system.

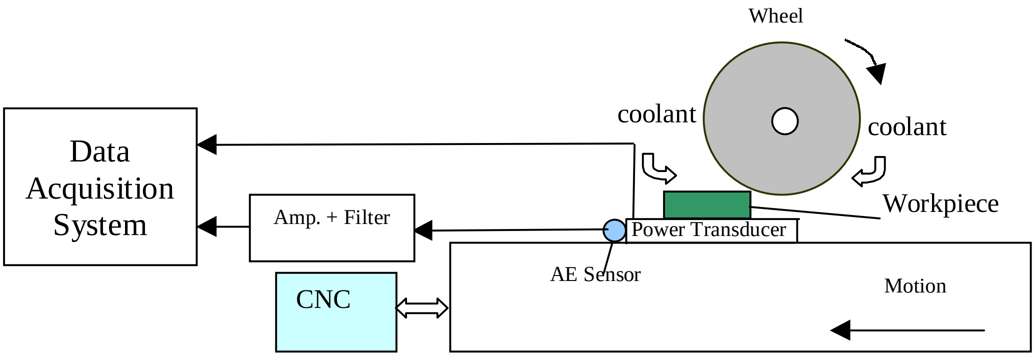

Figure 1 - The grinding apparatus

It has been noted that the raw signal is strongly autocorrelated. In fact, much of this autocorrelation is due to the sensor itself, whose function is aided by internal resonances. It is worth mentioning that adaptive (Wiener) whitening (Haykin, 1996, Proakis et al., 1996) was performed on these signals, but did not aid in detection of burn and was not pursued further. Details of the tests are shown in tables 1 and 2. In the case of the inconel workpieces, burn can be estimated only visually. In the case of the 52100 workpieces burn was assayed visually and through laboratory testing (nital etch and surface hardness). Burn, when it occurred, was to be found at or near the outfeed edge; this is due to coolant starvation from spray off this edge and away from the grinding interface.

Table 1. The parameters for the inconel workpieces. All workpieces were 76.5mm in length. Burn location refers to the distance from the infeed edge and the first visible signs of burn. In test 6 the workpiece was ramped in such a way that contact was not established until 21mm from the infeed edge

Test	Depth of Cut	Burn Location	Comments
1	0.025 in	65 mm	Slight burn
2	0.010 in	68 mm	Very slight burn
3	0.005 in	-	No visible burn
4	0.035 in	62 mm	burn
5	0.045 in	50 mm	Heavy burn
6	-	60 mm	Heavy burn, ramp cut

Table 2. The parameters for the 52100 workpieces. All workpieces were 78mm in length. Burn location refers to the distance from the infeed edge and the first visible signs of burn. Metallurgical softening is denoted by TB (temper burn); a hard Martensite layer is denoted by RL (rehardened layer).

Test	Depth of Cut	Burn Location	Comments
1	0.002 in	65 mm	slight pervasive TB and RL
2	0.010 in	68 mm	slight pervasive TB and RL
3	0.020 in	-	no burn
4	0.030 in	62 mm	Slight TB at end
5	0.040 in	50 mm	moderate TB at end; some at start
6	0.050 in	60 mm	heavy TB at end; moderate at start
7	0.070 in	60 mm	heavy TB, RL at end; heavy TB at start

3. THE SIGNAL PROCESSING

A number of statistical signal processing tools were applied to the data collected. Most of these, such as moments (e.g. kurtosis) and predictability (the output of an adaptive Wiener whitener), did not correlate well with grinding quality, and we do not report them here. For the most part an attempt was made to normalize with respect to AE power, since this can rise or fall for reasons having nothing to do with burn.

3.1 The Spectrum

It is natural to investigate the behavior of the power spectrum. To calculate this, we have used fast Fourier transforms (FFTs) of length 1024, and averaged the magnitude-squares of these according to the Bartlett procedure (Proakis et al., 1996). The power spectral density of received data before contact and during benign grinding are shown in Fig. 2. It is clear that active grinding is characterized by enhanced high-frequency power. In Figures 4 and 5 we show the short-time power-normalized spectrum (that is, the power spectrum estimated from a block of data, divided by the average AE power during that block). In these plots lighter shading corresponds to higher power at the given frequency and time; logarithmic pre-processing was performed to avoid dynamic range problems in these plots.

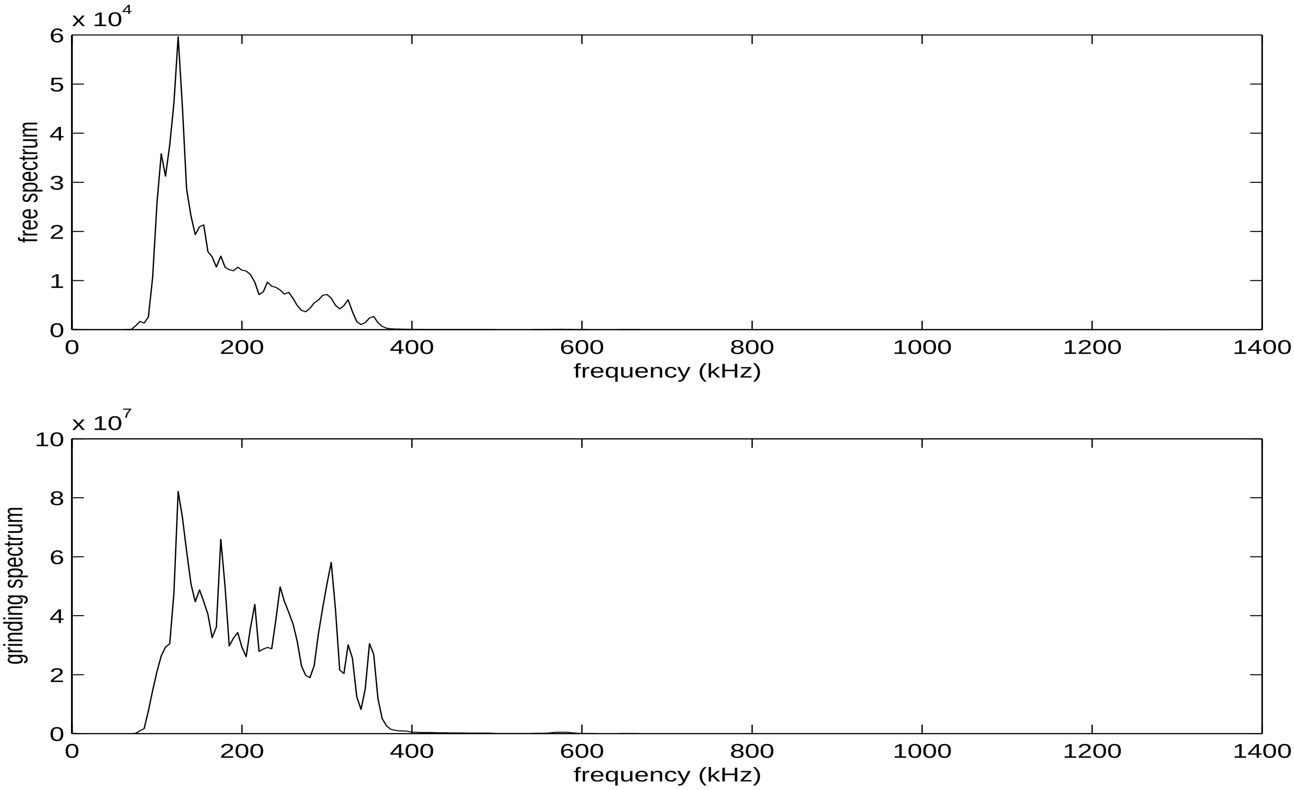

Figure 2 - Above: the measured autocorrelation coefficient from a typical grinding AE signal. Note the peaks at times corresponding to the reciprocal of the wheel rotational frequency. Below: a zoom view of the first autocorrelation peak.

3.2 The Nuttall Statistic

A data-processing step attracting a great deal of interest of late is Nuttall's "power-law" statistic [13]. The form of the statistic is

$$T(x) = \frac{\sum_k |X_k|^5}{\left[\sum_k |X_k|^2\right]^{2.5}} \qquad (1)$$

in which X(k) denotes the kth FFT output, and summation is over any specified range of frequencies. The denominator enforces that this statistic be power-independent; the exponent of five was found to be a robust choice for most applications.

Essentially, the power-law statistic measures a frequency-domain moment - in fact, if the exponents above were 4 and 2 instead of 5 and 2.5 this would be easily seen to be a kurtosis. Nuttall has derived this statistic based upon considerable analysis showing that its level is considerably enhanced when transient events (of almost any nature) are present in the block of data being processed. In grinding, physical phenomena such as coolant boiling, fracture (cracking), and simple grain-passage (the normal grinding wear mechanism) can all be thought of as transient burst-energy events, hence our motivation for exploring this statistic here.

3.3 Correlation 1: Wheel-Period Correlation

In Figure 3 is shown a typical AE auto-correlation signal. It is somewhat remarkable that the AE signature from one revolution of the wheel over the workpiece is highly similar to the AE signature from the next revolution - this is most likely due to the wheel/cutting profile remaining more or less constant. We use the value of this correlation "peak" both as a statistic in itself, and also as a measure of wheel rotation period. Again, remarkably, AE is therefore able to measure rotational wheel speed very accurately. We note that to measure the peak's height and position we have used three-point parabolic interpolation; from Figure 3 it is seen that the actual peak may lie in between two samples.

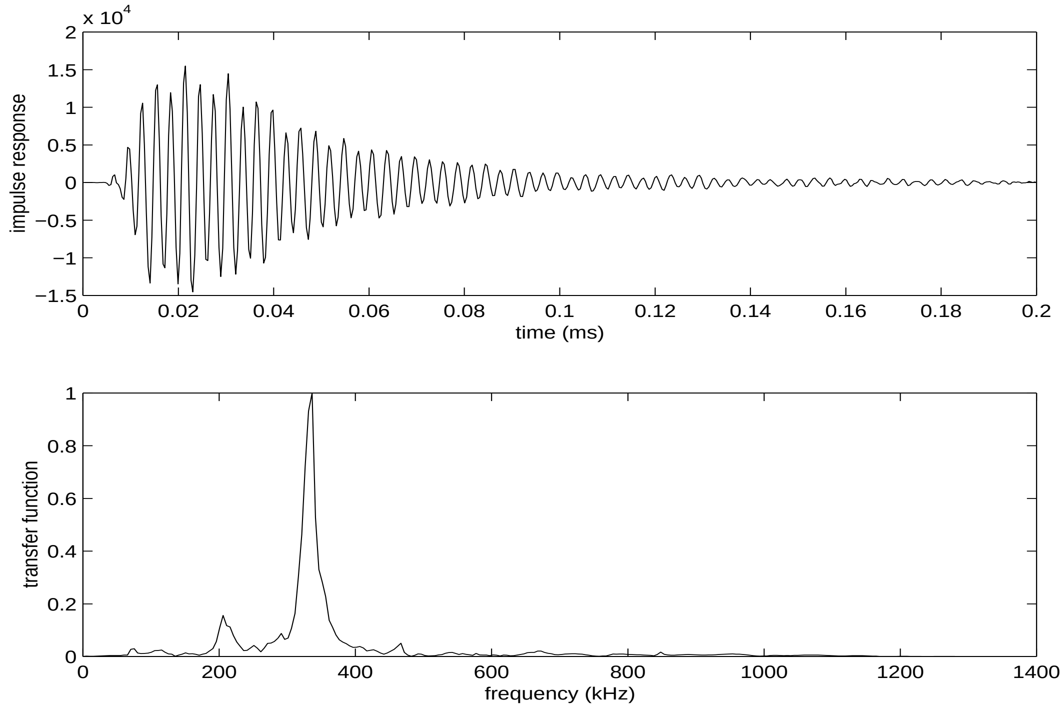

FIG. 3 – Above: the system response, as determined from “pencil-break” data, amplitude is in A/D units. Below: the system transfer function, units normalized to give maximum unity value.

The auto-correlation can be measured directly; but since this is computationally burdensome a fast alternative means was used [16]. Specifically, we estimate

$$\hat{r}(m) = \frac{1}{2N} \sum_{k=0}^{2N-1} |X_k|^2 e^{j2\pi km/2N} \tag{2}$$

For any m $\in$ {0,…,N-1}, where

$$X_k = \sum_{n=0}^{N-1} x_n e^{-j2\pi kn/2N} \tag{3}$$

meaning, in essence, that we take the 2N-point zero-padded FFT of a block of data of length N, take the magnitude-square, and then take the 2N point inverse FFT. Since 2N-point FFT can be calculated using $\vartheta[2N\log_2(2N)]$ operations, all auto-correlation can be determined very quickly.

3.4 Correlation 2: Wheel-Period Power Correlation

It is arguable that the auto-correlation measure described above is overly sensitive to random effects such as phase noise (it is unlikely that a wheel revolution corresponds to an integral number of AE sampling points) and grain slippage (a small wheel deformation can result in a large loss of correlation). Thus, we propose to perform the same operations, but instead on filtered power data. Specifically, in equation (3) the raw signal x_n is replaced by

$$y_n = \left(\sum_{l=-L+1}^{L-1} (1 - |l|/L) x_{n+l}^2 \right) - \bar{y} \qquad (4)$$

in which the mean value $\bar{y}$ is subtracted. It is anticipated that this statistic retains a more accurate and robust estimate of the wheel profile than the previous correlation. In our tests, we used the value L=10.

4. RESULTS AND DISCUSSION

Statistics from inconel tests 6 (angled cut; heavy burn) and from 52100 steel test 7 (heavy burn) are shown in figures 4 and 5, respectively.

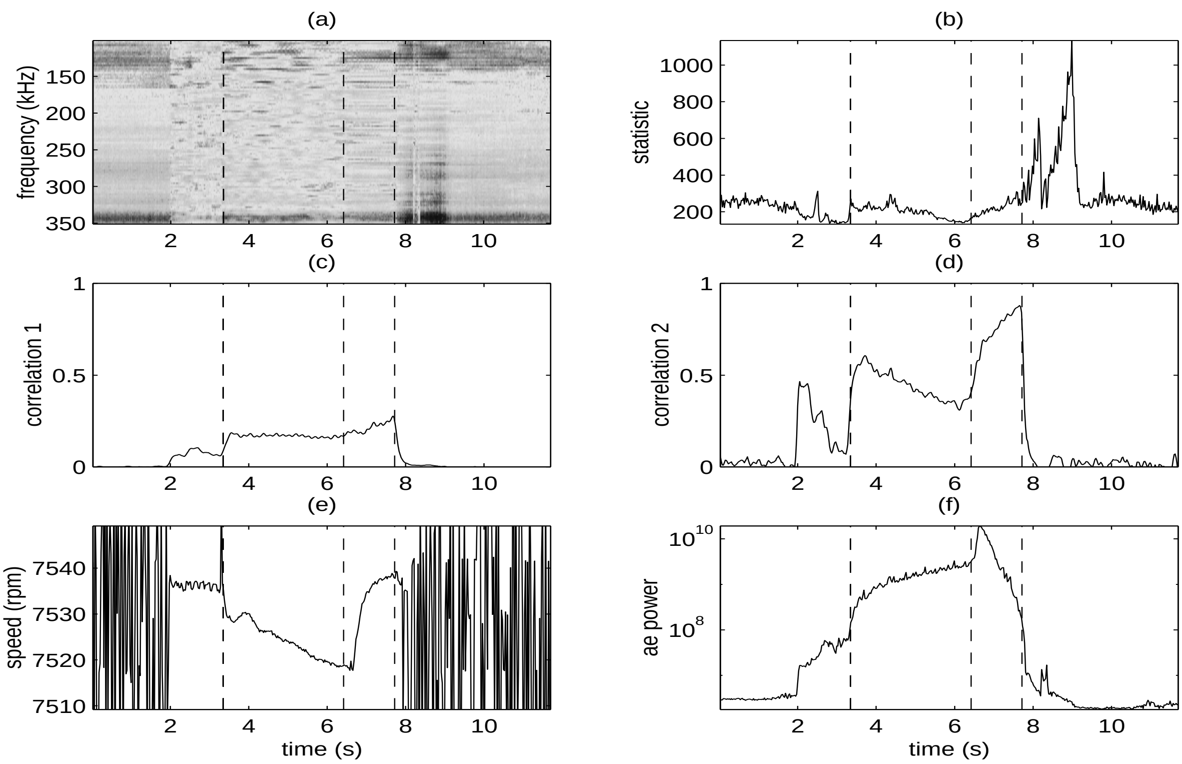

Figure 4 - Data from the sixth Inconel test. (a) normalized frequency spectrum. (b) Nuttall statistic. (c) wheel-period correlation. (d) wheel-period correlation. (e) wheel speed measured from AE. (f) AE power. The vertical dashed lines represent: time of lull contact; time of observed burn, time of end contact. As this was an angled cut, first and full contact times are coincident.

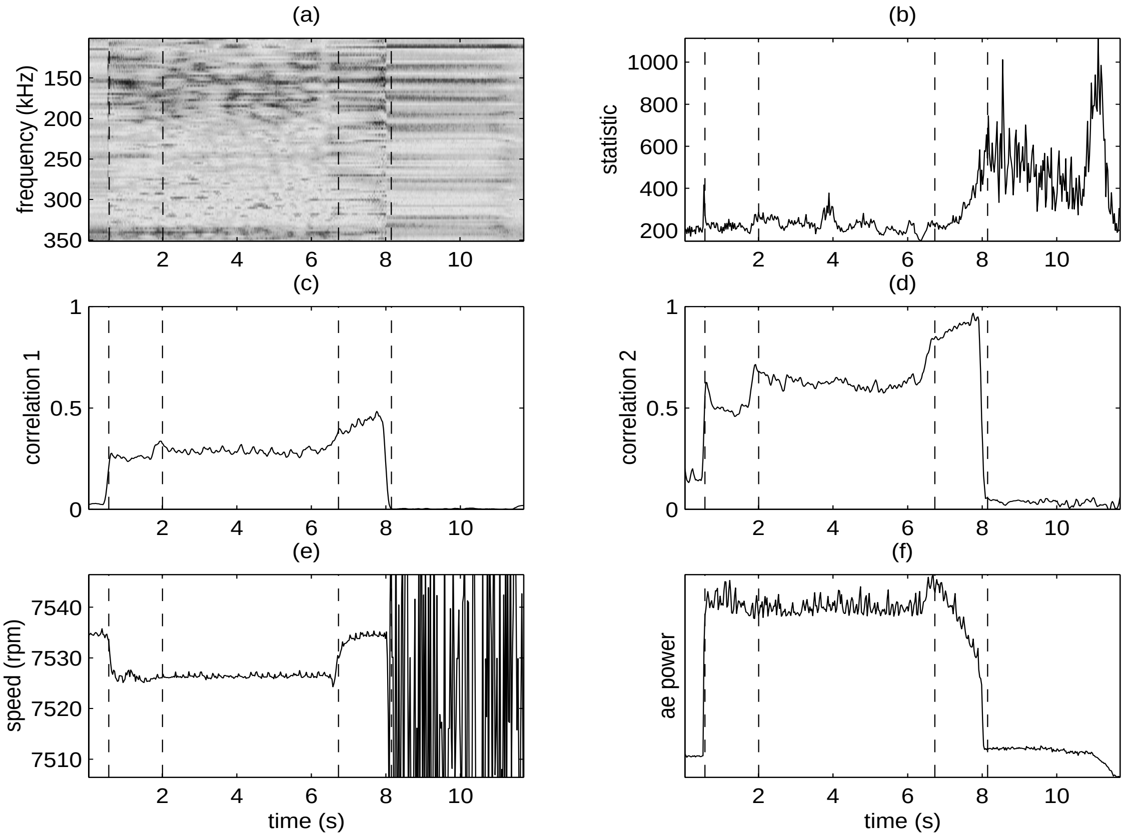

Figure 5 - Data From the seventh 52100 test. (a) normalized frequency spectrum. (b) Nuttall statistic. (c) wheel-period correlation. (d) wheel-period power correlation. (e) wheel speed measured from AE. (f) AE power. The vertical dashed lines represent: time of first contact; time of full contact; time of observed burn, time of end contact.

It is clear from the normalized spectrum that normal non-destructive grinding has a somewhat disordered or "dappled" spectrum; but at the onset of burn the spectrum remains relatively consistent. We note this feature, but as of yet have been unable to summarize it into a usable scalar statistic. The normalized Nuttall power-law statistic does not appear to offer any compelling evidence of burn.

It appears that burn is characterized effectively by increased wheel-period correlation; the effect is amplified, as expected, when the second (filtered power) correlation is examined. It is speculated that this is due to metallic softening during burn: the wheel "rubs" and "plows" rather than "grinds", and its change from revolution to revolution is concomitantly lower. Further evidence of this is available from the wheel speed data, in which it is evident that the wheel increases its speed -- the time between correlation peaks is lower -- when burn is occurring. (It is likely possible that this effect could be measured by a substantially less involved technique than high-rate AE; but we have noted its existence for the first time during our AE study.) Comparing inconel and 52100 plots it can be observed that correlation is greater in the latter than the former; this is as expected, since 52100 bearing steel is relatively soft and plastic. If wheel-period correlation is to be used as an indicator for burn, a relative increase rather than an absolute level should consequently be sought. The wheel-period power correlation statistic is shown for all grinds (except the first 52100 test, left off for reasons of space) in figures 6 and 7. Comparing this with the data in tables 1and 2 it is seen that burn correlates well with an increase in this statistic. The table data was mostly gathered through visual inspection; the statistical data appears to predict burn somewhat earlier (52100 test 5) and more often (52100 test 1) than the inspection data.

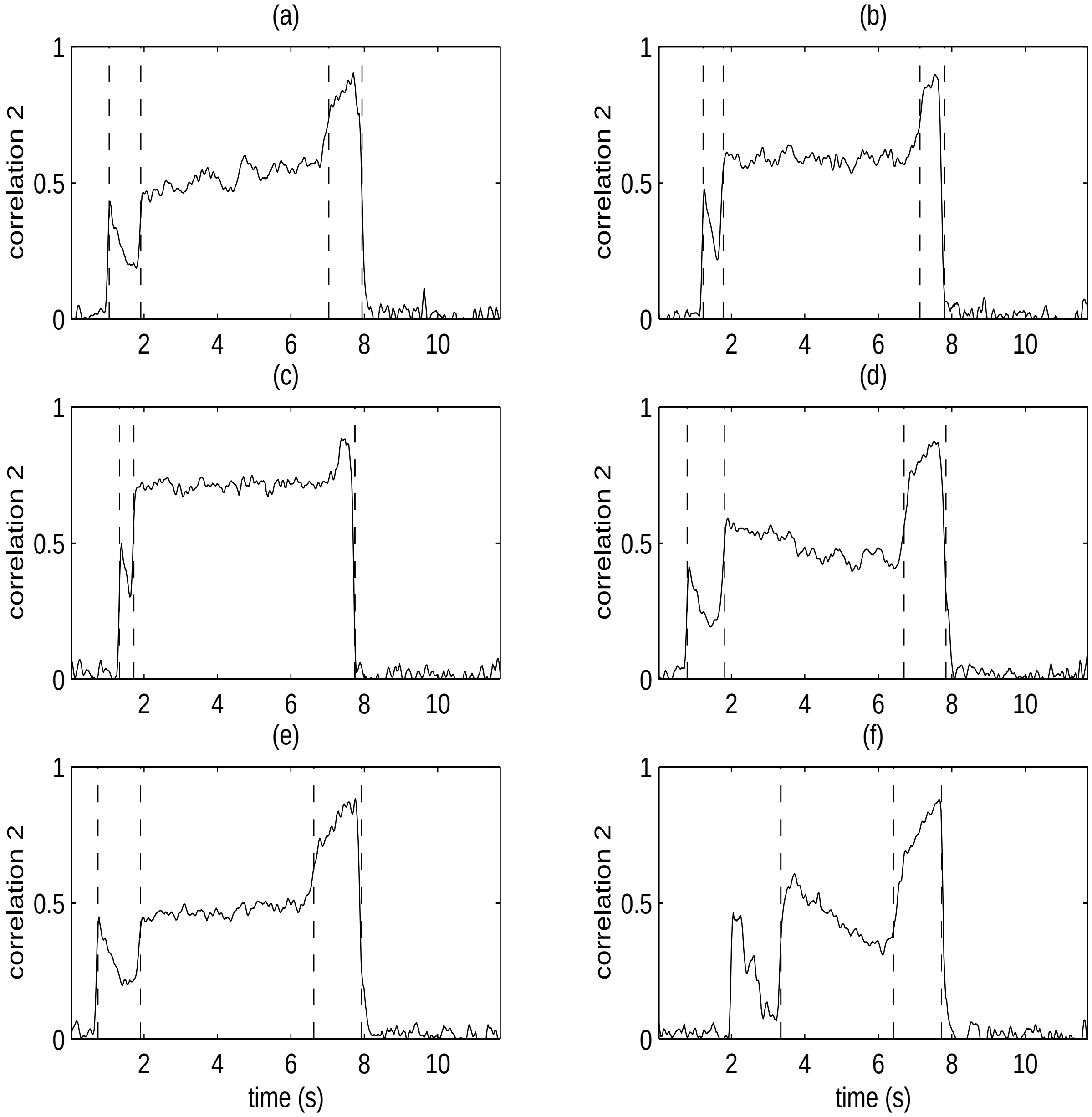

Figure 6 – Wheel-period power correlation from Inconel tests 1 through 6. The vertical dashed lines represent: time of first contact; time of full contact; time of observed burn, time of end contact. The first and full contact lines are coincident in test 6, the angled cut.

5. CONCLUSIONS

In this paper we have described analysis of high sampling rate AE from a series of grinding tests with the idea of finding a statistic indicative of workpiece burn. While our results are preliminary, it appears that the metallic softening accompanying burn causes the AE signal to change less from wheel revolution to revolution than would be observed if the metal were undamaged. This is observable as an increased correlation statistic, and also in a degree of self-similarity between short-time spectra. It has also been observed, somewhat surprisingly, that wheel speed (rotational velocity) can be determined quite accurately from AE data.

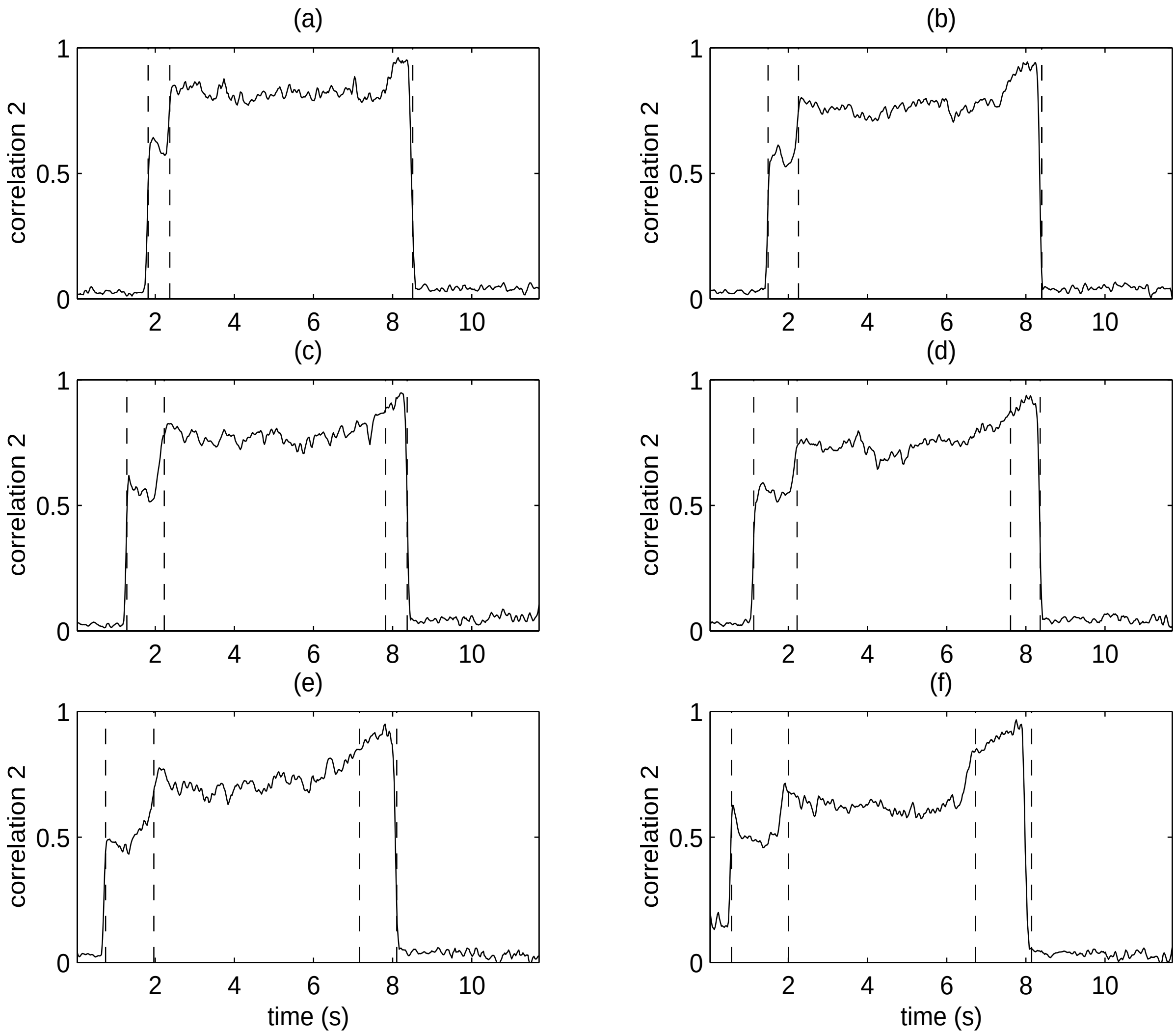

Figure 7: Wheel-period power correlation from 52100 tests 2 through 7. The vertical dashed lines represent: time of first contact; time of full contact; time of observed burn, time of end contact.

6. ACKNOWLEDGMENT

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