ELSEVIER

Journal of Materials Processing Technology 76 (1998) 192–197

Journal of
Materials
Processing
Technology

Tool failure detection based on analysis of acoustic emission signals

K. Jemielniak *, O. Otman

Warsaw University of Technology, Faculty of Production Engineering, ul. Narbutta 86, 02-524 Warsaw, Poland

Received 27 May 1997

Abstract

Acoustic emission (AE) is considered one of the main methods of on-line detection of catastrophic tool failure (CTF). Some strategies have claimed a subsequent increase of the root mean square value of the AE signal (AE_{RMS}) which in turn has been used as a measure of the CTF. However this measure was found to be not always sensitive to CTF. The aim of this paper is to present a method of catastrophic tool failure detection which uses symptoms other than the direct AE_{RMS} signal. The method is based on the statistical analysis of the distributions of the AE_{RMS} signal. The β distribution which was assumed in this study has been used with a density function of two parameters. The skews and kurtosis of the β distribution were the main measures employed. They were found to be highly sensitive to changes in tool condition and have given promising results with regard to chipping and tool breakage detection. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: Tool condition monitoring; Tool failure detection; Acoustic emission signals

1. Introduction

Tool condition monitoring (TCM) plays an important role in improving reliability and promoting automation of manufacturing processes. One of the important tools of TCM is the tool failure detection which includes cracking, chipping and fracture of the tool during machining. Several systems are commonly used, these are typically based on forces, acoustic emission, current and temperature [1]. The systems based on cutting forces are considered the most promising, however in spite of the availability of some commercial systems these are still considered not reliable enough, they require double checking by other different system. Furthermore the dynamometer is costly and its installation is rather inconvenient and could weaken the machine structure. Therefore some other approaches have been used for tool condition monitoring, among them is the acoustic emission (AE) measurement which has been applied and to a certain extent has been successful.

Acoustic emission signal is generally classified into continuous type and burst type. Various techniques are commonly used in analysing AE data such as count and count rate which is a measure of burst type AE events obtained by counting the number of times the AE signal exceeds a threshold voltage, spectral analysis, amplitude distribution analysis, autocorrelation function and root mean square (RMS) signal analysis [7]. In metal cutting the acoustic emission generated by the deformation process contains both the continuous and burst type AE signal. The raw AE signal usually contains high frequency components, therefore it can not be easily handled when using conventional signal processing equipment. An appropriate method for analysing the AE signal based on the root mean square of the signal (AE_{RMS}) is often used and it is suitable for use with the traditional signal processing systems with much lower sampling frequency [9]. However, one should be aware of the nature of the AE signals and be careful when extracting results from the system to avoid processing incorrect or distorted results. This has been studied in detail in previous work [6]. The RMS value of the AE signal, which presents the signal's energy and has a much lower frequency content, will be the basis of the analysis carried out in this work.

---

* Corresponding author. Tel.: +48 22 6608259; fax: +48 22 490285; e-mail: jemiel@wip.pw.edu.pl

PII S0924-0136(97)00379-8

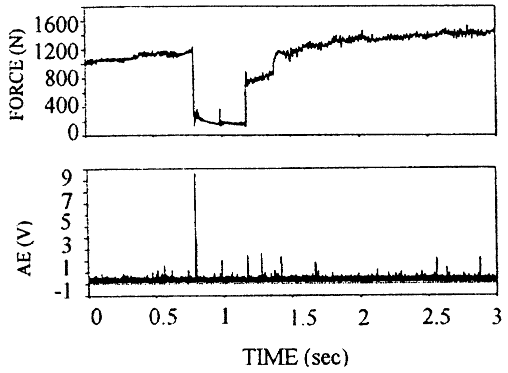

Fig. 1. Cutting force and AE signal in turning [8]

According to research [2,3,8,9] the catastrophic tool failure (CTF) is often accompanied by an eminent burst of an AE signal. Therefore the magnitude of the AE_{RMS} has been considered a very useful means of CTF detection, see Fig. 1. Similar results were obtained from experiments conducted in Warsaw University of Technology (WUT), however in some interrupted cutting tests the change in the AE_{RMS} signal course was not remarkable. This is particularly when minor tool fractures or chipping occurred. This does not mean that the AE_{RMS} signal did not change at all. In Fig. 2. a notable change of the AE_{RMS} course occurred just after the CTF is visible, however this can not be used directly as a measure of catastrophic tool failure detection. Therefore the aim of the research work undertaken in WUT was to develop a method of AE_{RMS} signal processing which enables the expression of this visual change in a mathematical form. In other words the task in hand was to establish an AE_{RMS} based measure(s) sensitive to subsequent changes accompanying the catastrophic tool failure.

2. Statistical analysis of the acoustic emission signals

One of the methods used in the AE signal processing is statistical analysis based on the distribution moments of the measured AE signal. It has been used in association with metal deformation, cracking and fracture and has been implemented as a means of understanding the current status of these materials and predicting their likely condition thereafter.

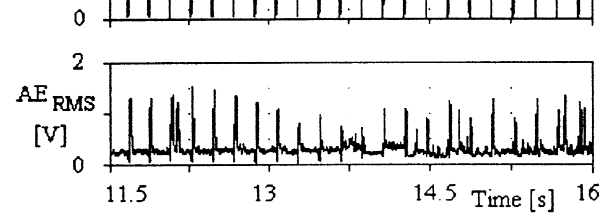

Fig. 2. Insignificant change in the AE_{RMS} signal course in the case of CTF (interrupted cutting)

The influence of tool wear on the AE_{RMS} signal distribution was investigated earlier by Kannatey-Asibu and Dornfeld [7]. They evaluated the appropriateness of using an assumed β distribution to characterise the RMS value of the AE signal regarding the degree of tool wear. Gabriel et al. [4] have reported that amongst other parameters of the AE signal the skew and kurtosis of an AE signal distribution was sensitive to the degree of tool wear.

The β function is given by:

$$\beta(r,s)=\int_0^1 AE_{RMS}^{r-1}(1-AE_{RMS})^{s-1}\,dAE_{RMS} \tag{1}$$

where r and s are parameters of the distribution given by [10]:

$$r=\frac{\overline{AE}_{RMS}}{\sigma^2}(\overline{AE}_{RMS}-\overline{AE}^2_{RMS}-\sigma^2) \tag{2}$$

$$s=\frac{1-\overline{AE}_{RMS}}{\sigma^2}(\overline{AE}_{RMS}-\overline{AE}^2_{RMS}-\sigma^2) \tag{3}$$

where $\overline{AE}_{RMS}$ is the mean and σ^2 is the variance. Skew and kurtosis are parameters of the distribution. They can be given as:

$$S_B=\frac{2(s-r)}{r+s+2}\left(\frac{r+s+1}{rs}\right)^{1/2} \tag{4}$$

$$K_B=\frac{6\{(r-s)^2(r+s+1)-rs(r+s+2)\}}{rs(r+s+2)(r+s+3)} \tag{5}$$

The skew measures the symmetry of the distribution about its mean value while the kurtosis is a measure of the sharpness of the peak. A positive skew generally indicates a shift of the bulk of the distribution to the right of the mean, and a negative skew indicates a shift to the left. A high kurtosis value implies a sharp distribution peak (concentrated in a small area) while a low kurtosis value indicates essentially flat characteristics.

Therefore if the $\overline{AE}_{RMS}$ mean and variance σ^2 of a distribution are known, the parameters r and s can be obtained (Eqs. (2) and (3)), and accordingly the values of the skew S_B and kurtosis K_B can be calculated (Eqs. (4) and (5)).

The suitability of using these variables, i.e. the skew and kurtosis to the catastrophic tool failure (chipping and breakage) detection will be evaluated.

3. Experimental set-up

Cutting tests were performed using TUD-50 lathe machine. An acoustic emission sensor (Kistler 8152A1) and a piezotron coupler (Kistler 5125A1) were used to measure and pre-process the AE signal generated by the cutting process. The coupler enables amplification, filtering and RMS conversion of the AE signal. A dynamometer (Kistler 9263) was used to measure the three force components (feed force F_f, passive force F_p and cutting force F_c). Catastrophic tool failure is always accompanied by characteristic patterns of the cutting forces [5]. Therefore their measurements were used here as reference signals to indicate when the CTF has actually occurred. The work material used was steel 45 bars. A 2 cm wide longitudinal groove has been made in some bars to provoke interrupted cutting in order to encourage tool failure. Two types of carbide inserts were used, SNUN-120408 S30S (ISO P30) and TNMG-160408 NT25 (TiC–TiN coated). The tests were performed under the following cutting parameters: depth of cut = 2.5–4.0 mm, feed = 0.3–0.8 mm rev^{-1} and cutting speed = 120–300 m min^{-1}. The sampling frequency was 2 kHz. A schematic illustration of the experimental set-up is shown in Fig. 3.

4. Experimental results and discussion

The distribution moments calculated from the discrete data and based on the β distribution were assessed in this study. The analysis of the AE measured data was essentially based on the digitised $\mathrm{AE}_{\mathrm{RMS}}$ signal. The signal was divided into samples of equal number of data. Two main variables were obtained, the mean ($\overline{\mathrm{AE}}_{\mathrm{RMS}}$) and the standard deviation Σ. These two variables were then used as inputs to Eqs. (2)–(5) to obtain the parameters of the β function r, s and consequently the values of the skew S_B and kurtosis K_B. As the signal originating from a tool failure (chipping or fracture) occurs in a very short time the number of data points in each sample has been set to the minimum possible so that the precise changes in the tool condition can be detected effectively. In the case of tests conducted in interrupted cutting the number of data points/sample should contain the measured AE data from at least one full revolution of the workpiece, see Fig. 4. Such arrangement is appropriate as it includes in each sample the acoustic emission generated from the tool engagement and disengagement with the workpiece due to the groove made in it. The impact on the workpiece due to tool engagement is accompanied by acoustic emission signals of relatively high amplitude. This should be taken into consideration and has to be included in each sample. Therefore the number of data points taken in each sample is a function of both the cutting speed and the sampling frequency of the $\mathrm{AE}_{\mathrm{RMS}}$ signal. To reveal more information from the AE measured data, a compound sample analysis in an overlapping mode was employed, see Fig. 4. Thus the degree of data processing is determined in accord, i.e. the lower the step/sample ratio the better the expected results. However very low ratios necessitate high processing time which results in slow detection of the CTF and furthermore it has been realised that further shortening of the step does not help very much in revealing more information from the AE data. Satisfactory results were obtained when the step/sample ratio = 1/8.

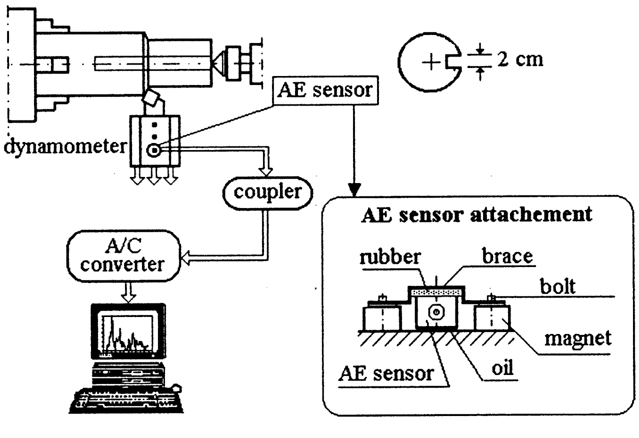

Fig. 3. Schematic illustration of the experimental set-up.

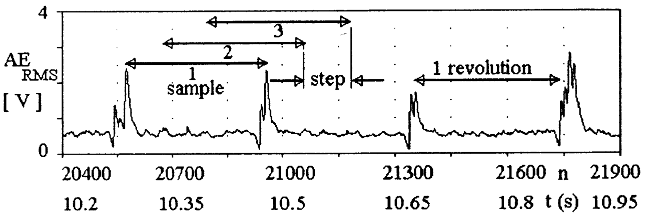

Fig. 4. Overlapping distributions

Since the resulting measures from the distributions were obtained by the end of each individual sample a delay in the CTF detection is expected. The time delay is dependent on two variables: the number of data points taken in each sample and the step. In the case of interrupted cutting where the number of data points/sample = number of AE data measured from one revolution of the workpiece, the time delay will be at least equal to the time span of one workpiece revolution. However in the case of continuous cutting where less data points/sample can be used, less time delay is expected. This problem will be confirmed with an example later on.

In the case of catastrophic tool failure, significant changes in the force courses were always observed. They were often accompanied by a consequential change in the magnitude of the $\mathrm{AE}_{\mathrm{RMS}}$ signal. In some cases when interrupted cutting tests were conducted the

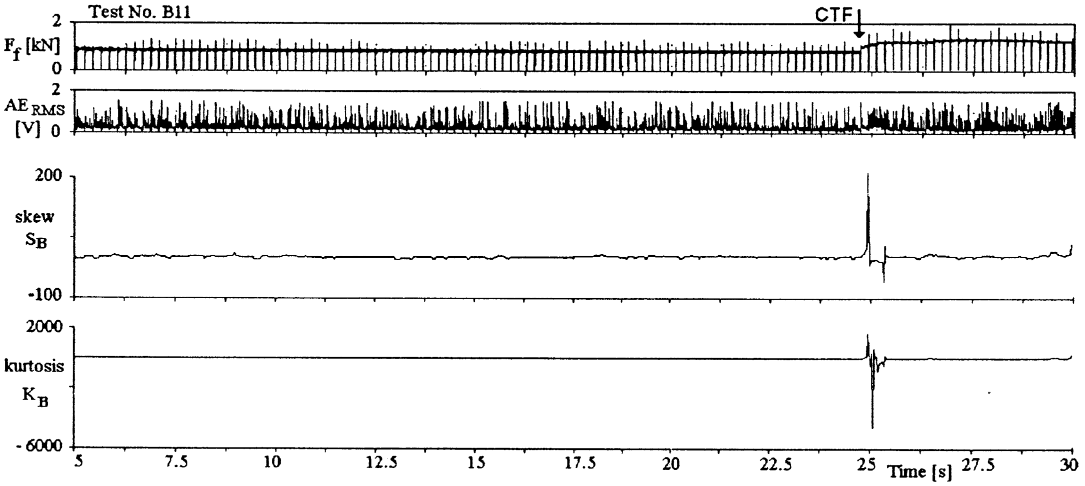

Fig. 5. Suitability of CTF detection by means of skew and kurtosis.

change in the AE_{RMS} signal was not evident which makes it inappropriate to be used directly for CTF detection. An example of the interrupted cutting case when turning steel 45 with SNUN 120408 S30S (ISO P30) tool is shown in Fig. 5. The effect of tool engagement and disengagement with work material due to the interrupt is clearly seen in both the feed force F_f and the AE_{RMS} courses. Instantaneous drops in the values of F_f in each workpiece revolution due to tool disengagements and significant rises in the magnitude of AE_{RMS} due to engagements with work material. A CTF has occurred in this test. The change in the cutting force signal course due to the CTF is significant. It can be seen that the change in the AE_{RMS} value at the incident is not consequential which confirms the above mentioned argument about the inappropriateness of using this symptom directly to detect CTF in such cases. When the skew S_B and the kurtosis K_B of β distribution were assessed a significant change at the moment of tool failure has occurred on both courses of S_B and K_B. Two successive abrupt changes in both symptoms were recognised, these are attributed to the instability of the cutting process at this particular moment when the tool failure occurred. Moreover, all the disturbances appeared in the AE_{RMS} course due to tool engagement with work material having disappeared in both S_B and K_B courses. These are ascribed to averaging the AE_{RMS} signal values. Therefore the sensitivity of these measures i.e. the skew and kurtosis to subsequent changes in cutting tool condition was the main criterion used to investigate the catastrophic tool failure. Thus, thresholds of certain limits can be set to trace both the skew and kurtosis courses, when these are violated instantaneously by both courses a catastrophic tool failure case is recognised.

One of the crucial problems to be considered in the catastrophic tool failure monitoring is the timing of detection. It has been stated earlier that a delay in CTF detection is expected. An example is shown in Fig. 6. A CTF was detected by the passive force F_p at ~ 7.45 s. When the signal analysis was done without overlapping

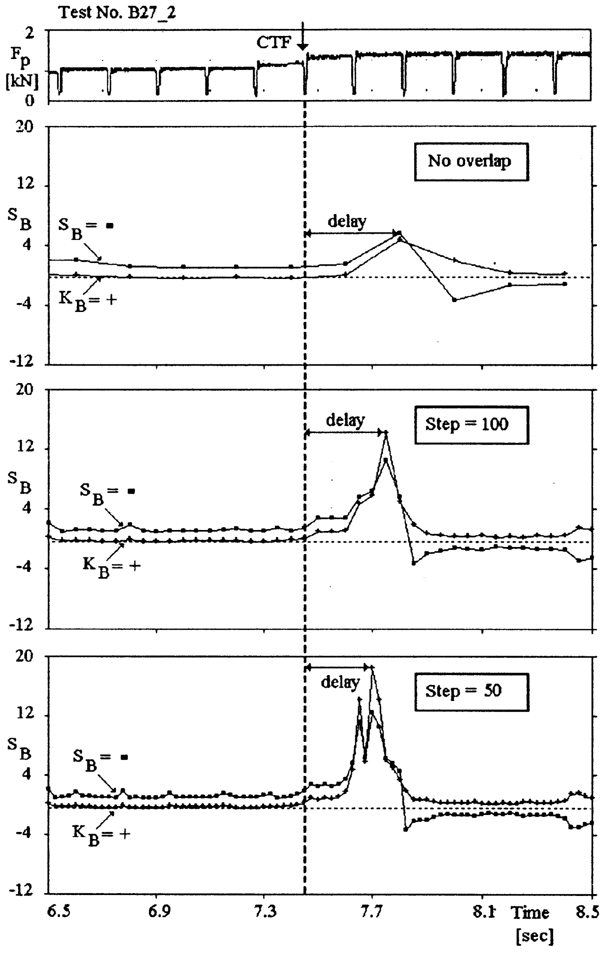

Fig. 6. The effect of using overlapping samples on the precision of CTF detection.

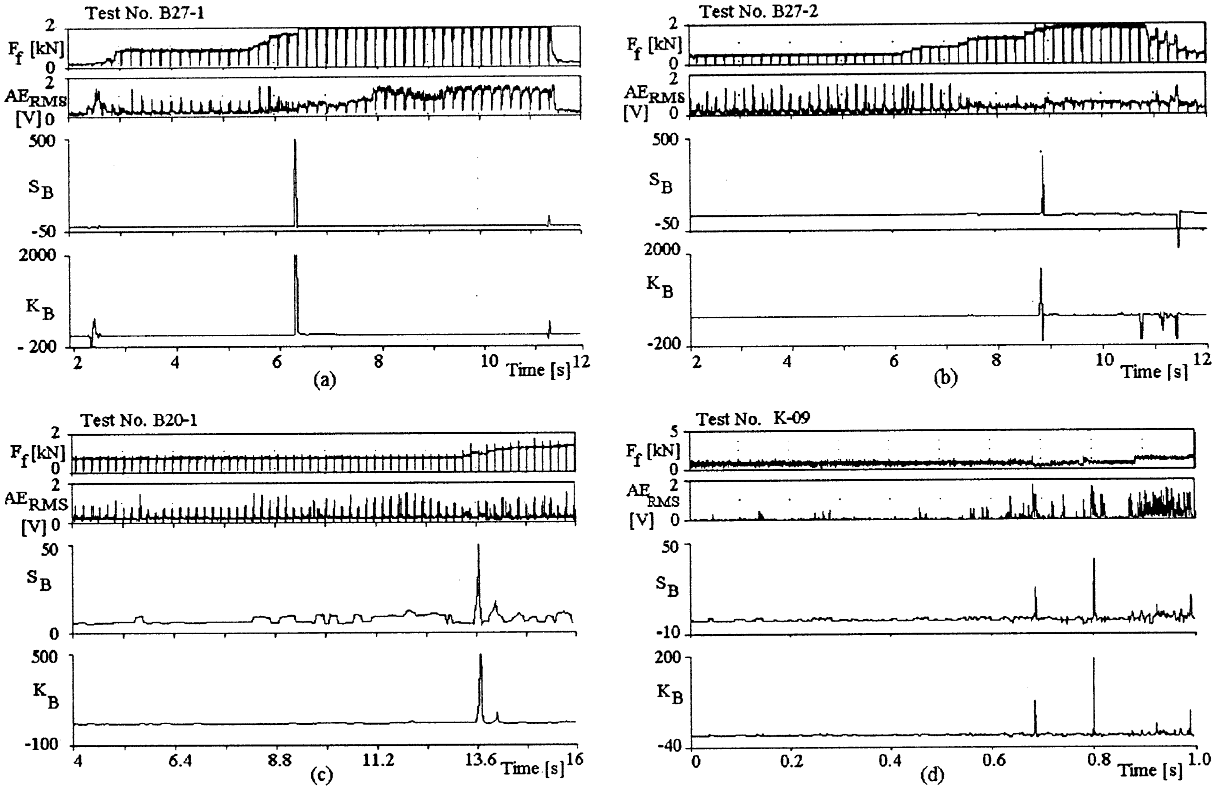

Fig. 7. Examples of CTF detection by the skew and kurtosis.

samples (in this test the cutting speed was 300 rpm, thus No. of data/sample = 400) the CTF was detected by both the skew and kurtosis at ~ 7.83 s, i.e. about a 0.38 s delay. However when overlapping samples at step = 100 were used the CTF has been detected at 7.77 s, the delay was lowered to 0.32 s. Less delay was encountered when the step was lowered to 50 data points (0.27 s delay was registered). Therefore the lower the step the less delay is expected and consequently the faster the CTF detection.

Several tests in both continuous and interrupted cutting were conducted to confirm the validity of the method. Some examples are given in Fig. 7. Both the skew and kurtosis proved to contribute to high rates of catastrophic tool failure, however test statistics have shown that the contribution of the skew to the CTF is slightly higher. Some faulty detections have been encountered, these are mainly attributed to the following reasons:

- Distorted AE signals due to preamplifier overload for example were found to be one of the prime causes of faulty CTF detection. Thus the preamplifier gain should be carefully adjusted to the sensor sensitivity and strength. It is recommended that the value of the AE_{RMS} signal should be within certain limits that would keep the values of the skew (S_B) between ± 500 and the values of the kurtosis (K_B) between ± 2000.
- Some defects in the workpiece material such as hard spots due to poor quality of manufacturing, have the tendency to cause instantaneous generation of high amplitude AE signal during the cut. This results in consequent changes in the values of the predominant symptoms and accordingly in faulty detections.
- Runout of work material, tool entering workpiece and end of cut were found to generate signals similar to those arising from tool breakage, see Fig. 7a,b. Therefore it is necessary to give greater attention to such problems when setting an acoustic emission based strategy.

5. Conclusions

The acoustic emission measurement was applied to in-process detection of the catastrophic tool failure. The detection was embedded in the statistical analysis of the metal cutting acoustic emission based on monitoring the skew and kurtosis of an assumed density function of distribution. In conclusion:

- The root mean square of the acoustic emission signal did not always show significant change in magnitude at the moment of catastrophic tool failure. This was experienced particularly when conducting interrupted cutting tests.

- Skew and kurtosis of an assumed β distribution for the AE_{RMS} signal were found to exhibit good sensitivity to catastrophic tool failure. Obtained results have shown good correlation of skew and kurtosis to the CTF which make them promising symptoms of CTF monitoring.
- The precision of tool failure detection depends on the number of AE data points taken in both the sample and the step. The lower the value of the step/sample ratio the more precise the expected results. Furthermore, implementing overlapping samples reveals hidden information in the AE signal which can be useful for tool condition characteristics.

References

[1] G. Byrne, D. Dornfeld, I. Inasaki, G. Ketteler, W. König, R. Teti, Tool condition monitoring (TCM)—The status of research and industrial application, Ann CIRP 44 (2) (1995) 541–567.

[2] C. Cavalloni, New Acoustic Emission Sensors for In-process Monitoring, Kistler Instrumente AG Wniterthur, 1993.

[3] E.N. Diei, D. Dornfeld, A model of tool fracture generated acoustic emission during machining, Trans. Am. Soc. Mec. Engrs. J. Eng. Ind. 109 (1987) 227–234.

[4] V. Gabriel, J. Matusky, A. Prušek, J. Žižka, Study of Machining Pocess by Acoustic Emission Method, Proceedings of the IV International Conference on Monitoring and Automatic Supervision in Manufacturing, Miedzeszyn, CIRP, 1995, pp. 143–148.

[5] K. Jemielniak, Detection of cutting edge breakage in turning, Ann. CIRP 41 (1) (1992) 97–100.

[6] K. Jemielniak, O. Belgassim, Characteristics of Acoustic Emission Sensors Employed for Tool Condition Monitoring, Proceedings of VII Workshop on Supervision and Diagnostics of Machining Systems, Karpacz-Poland, CIRP March 1996, pp. 241–252.

[7] E. Kannatey-Asibu, D. Dornfeld, A study of tool wear using statistical analysis of metal cutting acoustic emission, Wear J. 76 (1982) 247–261.

[8] J.M. Lee, D.K. Choi, C.N. Chu, Real-time tool breakage monitoring for NC turning and drilling, Ann. CIRP 43 (1994) 81–84.

[9] T. Moriwaki, Detection of cutting tool fracture by acoustic emission measurement, Ann. CIRP 29 (1) (1980) 35–40.

[10] D. Whitehouse, β functions for surface typology, Ann. CIRP 27 (1978) 491–497.