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ON USE OF ACOUSTIC EMISSION IN MONITORING OF UNDER AND OVER ABRASION DURING A WATER JET MILLING PROCESS

Water jet milling process is a new emerging technology with many interesting applications. Low cutting forces, no thermal distortion, process flexibility and ability to machine difficult to cut materials make it very attractive for many technological operations. However, its wider application is hindered by lack of proper solutions of process monitoring that would allow accurate control of the material removal process. The research contributions so far focused on use of acoustic emission, thus the purpose of this paper is an evaluation of the proposed strategies and analysis of applicability of acoustic emission for this purpose. An extensive amount of AE data was collected during waterjet machining with various feed rates, abrasive flows, and pump pressures, and analyzed with the aim to determine whether there exists any feature of the AE signal correlated with under- and over abrasion. Monitoring and control of removal rate is possible only if it is possible to discriminate between AE signal samples originating from different states of the abrasive process. In this paper I present results based on extensive one-way ANOVA study of the AE samples, showing, that the standard AE signal features proposed in the literature – the energy and statistics of the AE signal do not allow such discrimination, and are not suitable to monitor abnormalities of the abrasive process. The research covers also principle component analysis of the AE signal energy performed in the aim to study if there exists any subset of the energy allowing better discrimination between the investigated process states.

1. INTRODUCTION

The intensive competition faced on the global markets creates enormous pressure to develop and implement new manufacturing processes. The processes should be more flexible, faster, more accurate and more energy efficient. It is particularly challenging today to find ways to improve process control methods allowing better quality, and enhance the utilization of production resources. One of the new emerging production processes with great potential is abrasive water jet milling. It has numerous advantages such as low cutting forces, no thermal distortion and extended flexibility. Also applicability to machine difficult to cut materials makes it very attractive for many technological operations. However, its wider application requires development of proper solutions for process monitoring allowing more accurate control of the material removal process.

So far research contributions reported in literature were focused on use of acoustic emission as the most promising approach [6]. The purpose of this paper is to review these

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contributions and evaluate applicability of the acoustic emission signal for this purpose. The focus is put on checking the possibility to use the AE signal for on-line detection of under- and over-abrasion during the process. This, together with already known possibilities of using AE to on-line measuring differences in pressure and abrasive flow [7], [8], [15], would make it possible to implement proper control strategies for the abrasion, achievement of smoother removal rates and better surface quality.

The signal analysis method for examining the discrimination capability of the AE signal in AWJ (Abrasive Water Jet) process monitoring will be described in detail to provide a clear picture regarding its applicability, accuracy and dissimilarities to the previously reported methods [6], [7], [8].

Acoustic emission (AE) is used in a wide range of monitoring applications e.g. for monitoring of cutting process, tool wear, chip forming, surface of the workpiece, chatter detection, and even certain aspects of machine tool condition [1-19]. Considering the wide span of applications, AE is a very interesting technology for implementing multipurpose monitoring strategies [18].

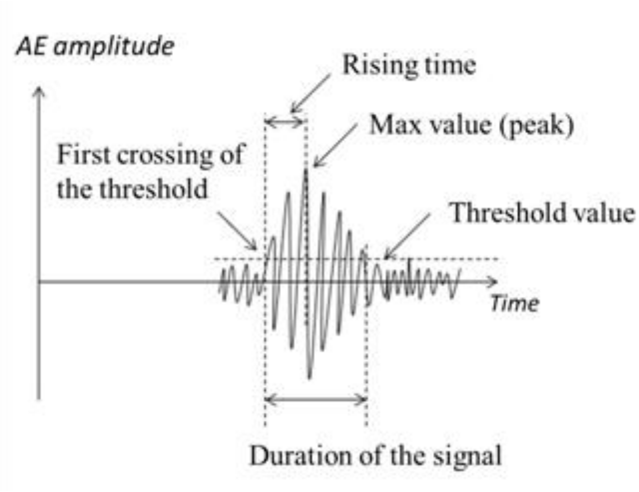

Fig. 1. The basic features of a “burst” type acoustic emission event

An acoustic emission signal (AE) is a high frequency stress wave originating from deformation zones, generated by rapid release of strain energy. During metal cutting, AE comes from many different sources: dislocation of crystals due to elastic and plastic deformations inside or on the surface of the workpiece, residual stress, friction between tool chip and workpiece, phase change temperature, chip strike, break, friction, or collision, chipping, build-up edge, chip spalling of tool material, and the like [19]. In AWJ the jet flow turbulences and cavitation is a considerable source of AE emission. Characteristics of AE waves are also influenced by machine tool dynamics and selected cutting parameters [20]. In addition, the generated waves are damped, reflected, interfering with each other, and in all possible ways distorted before they reach an AE sensor. Furthermore, part of the energy is lost due to fluid damping, so getting information from these signals is not trivial.

AE sensors were originally developed to measure single acoustic events of "burst" type, for nondestructive tests to analyze structural defects (see Fig. 1), and were used to measure certain parameters of AE events such as duration time, rise time, zero-crossing count, and maximum value. In these types of experiments the background noise is quite low, and it is easy to compensate for it using a proper threshold value. When applied to monitor abrasive jet processes, the measured AE signal is of continuous character, where a new AE event starts before a previous one dies out. To get information of interest from such "continuous" AE signal is challenging, but not impossible, as in practice there always is a dominant source of AE which in the end will determine the general characteristics of the AE signal. AE sensors are easy to install. Usually they are attached to workpiece surfaces, but there are also wireless solutions available, which allow transmission of the AE waves from the process to the transducer trough the water jet or simply trough the cooling water. This opens for measurements close to the studied process [1]. Also, in opposition to the case with force measurement, the AE sensor doesn't affect the stiffness of the machine.

There are several models of AWJ process available in the literature, and may be adapted for the purpose of monitoring and control. Some of them focus on explanation of action of the individual abrasive particles, and some on relation between process parameters like depth and shape of cut, surface roughness, and process parameters. More detailed modelling involves also models of the hydrodynamic effects in the flow in the kerf, liquid phases, the jet damping, particle distribution, the jet boundary conditions, and material properties.

2. EVALUATION OF CURRENT RESEARCH ON USE OF ACOUSTIC EMISSION IN WATER JET PROCESS MONITORING

Many researchers state that studying acoustic emission from machining processes may be successfully used for building better understanding of the involved process mechanisms [1], selection and closed loop control of process parameters [4], [6], indication of depth of penetration [2], [22] monitoring of tool wear [18], monitoring of grinding wheel wear and other applications. This indicates wide possible applicability of AE in monitoring of AWJ processes.

Beyond the material properties, the critical parameters influencing the AWJ process are the pump pressure, diameters of the orifice and the nozzle, the stand-off distance, the angle of jet impact, the abrasive flow rate and grain size, the exposure time (nozzle feed rate), and the impact of reflected jet flow [1].

A vast number of signal analysis methods were used by the researchers in the past to extract AE signal signatures correlated with process parameters, as summarized in the list below:

1. Peak-to-peak, mean, power, RMS, standard deviation, skew , kurtosis.
2. Ring down count (number of times the signal burst crosses threshold level).
3. Pulse width (percent of time the signal remains above the threshold).
4. Burst rate (number of times the RMS signal exceeds preset threshold per second.
5. Correlation analysis.

6. Beta distribution.
7. ARMA (Autoregressive Moving Average) models.
8. Principal component analysis, PCA (Karhunen–Loeve transformation).
9. Singular spectrum analysis, SSA (division of signal to trend, oscillatory component and noise).
10. Permutation entropy (examination of signal variability).
11. Fourier Transform, FFT.
12. Wavelet Transforms, WT.
13. Hilbert-Huang Transform, HHT.

Kovacevic et al. [1] investigated AWJ drilling process and used AE to build up an understanding of material removal mechanisms. The performed signal analysis was based on power spectrum density of an ARMA (2, 1) model. ARMA(p, q) – Autoregressive Moving Average model used to describe signals (time series) in terms of two polynomials – one for auto-regression and the second for moving average; p is the order of the autoregressive part, and q is order of the moving average part. They found, that the damped natural frequencies derived from the two roots are related to the impinging jet and the rebounded jet respectively. They also found, that area under the PSD (Power Spectral Density) curve, computed on the ARMA model, exhibits the same trend as the penetration rate.

Mohan et al. [2] reported that only a part of the energy delivered by the jet is participating in the material removal process – a considerable part of the input energy leaves the process as a backflow of abrasives, water and wear particles, or is lost in another way. As the performance evaluation of the material removal process requires understanding of the energy distribution mechanism, they developed a corresponding energy budgeting model considering mass and velocity of the mixture, exposure time, geometry of the nozzle, traverse rate of the machining head, and the pump pressure. As the model parameters are measurable, their model allows calculating the amount of energy dispersed during the process. The energy may be then quantified by AE signal measured as its PSD of ARMA (4, 3) model. In their experiments portion of dispersed energy varies between 60-90% of the input energy, depending on the erosion depth, and the input energy it selves. They reviled that also the abrasive mechanism (ductile vs brittle) influences the dissipation. Frequency analysis showed also a correspondence of one of the characteristic frequencies with the average number of the abrasive particles in the jet flow per time unit (this observation could not be confirmed by my own research). Yet another interesting observation was that at higher pump pressure the energy of AE signal was affected mostly by the abrasive mechanism (cracking and micromachining), and at lower pressure by hydrodynamic factors (higher water flow) like turbulence and cavitation. As they have shown the measured energy of acoustic emission is proportional to the square of the dissipated energy (with the determination coefficient R^2= 0.95) – a result confirmed also by other researchers [3].

Marinescu, et al. in a series of articles [6],[7],[8] present a concept of “transfer rate of energy”, TRE, which couples energy delivered to the machined workpiece as waterjet energy to the resulting abraded volume. The waterjet energy is presumed to be proportional to the energy of the acoustic emission signal measured on the work piece during the cutting process. This relationship is shown in equation (1).

$$TRE = \frac{\text{Acoustic Emission Energy}}{\text{Abraded Area} \times \text{Feed Rate}} = Constant \tag{1}$$

The problem in my opinion is that even if intuitively this relation might seem reasonable, it is not feasible. It is simply not possible to separate the acoustic emission energy generated during abrasive removing of a certain distinguishable volume of the material. The problem is explained in the Figs. 1 and 2 below. In the experiment setup described in [6], the nozzle with diameter of 1mm is moving with a certain feed rate along the workpiece and abrade a ”trench”. During this process the emitted acoustic emission is

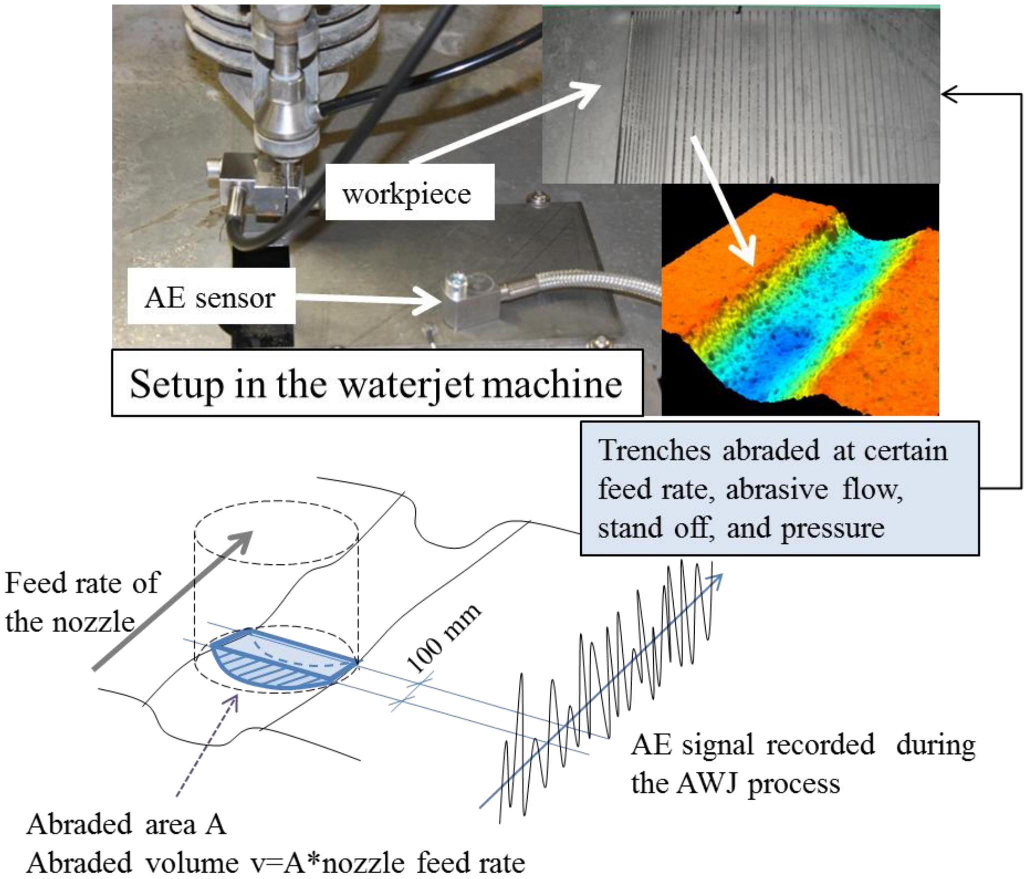

Fig. 2. Experiment arrangement. Abraded trench and AE recorded during the AWJ machining

measured and its energy estimated. After machining, the abraded trench is scanned using a confocal microscope and the abraded volume computed (which is the denominator in the eq. 1). The metrology resolution is 100microns in each direction. As the feed rate is known, it is tempting to associate the abraded volume rate (area of abraded footprint x feed rate, marked red in Fig. 2), with the acoustic emission energy measured in a time interval corresponding to the 100microns distance (in the case of feed 1000mm/min, the time interval would be 6milliseconds). However, as it may be realized from Fig. (3) such an association is not possible.

The nozzle has a certain inner diameter, and the abrasive particles hit the workpiece within the whole area below the nozzle, and not only the considered volume fragment. The AE events collected during a certain, small time interval (e.g. 6 milliseconds as mentioned above) comes from the whole area under the nozzle, and cannot be correlated with a measurable volume of removed material (see Fig. 3). Another problem with the TRE concept is that in accordance with [2],[3],[4] and [5] and my own research, the waterjet energy is not directly proportional to the measured energy of acoustic emission, as claimed in [6].

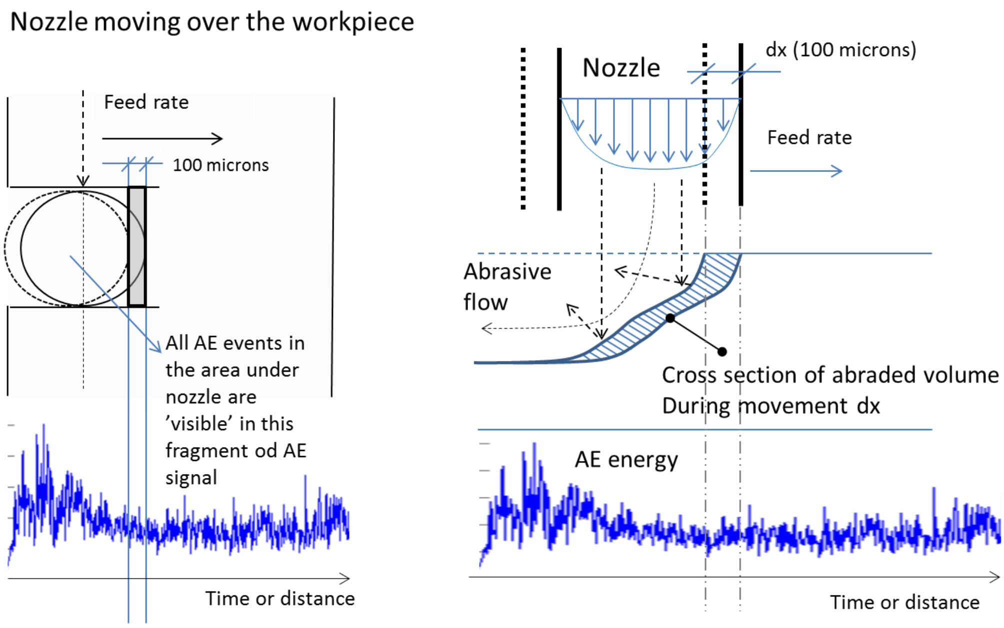

Fig. 3. A slice of the abraded volume cannot be related to the energy used for its removal, as this energy is dispersed, unknown part of the total AE energy between point1 and 2

An interesting model of abrasive water jet cutting process is presented by Deam et al. [4]. The model (see Fig. 4) shows that feedback in the process (influence from previous particles impact up–stream) is responsible for fluctuations in the local curvature of the cutting face (the surface roughness), and cannot be fully eliminated by more precise control of process parameters. The model shows also, that the roughness is growing with length of the face arc(ϕ), and not so much with variation in the jet conditions: variation in the jet speed, abrasive flow, feed rate, etc. This implies that we should expect a high 'natural' fluctuation in the measured AE signal.

A recent research performed by Hloch et al. [5] reviews the applications of AE in monitoring of the AWJ process presented in literature, and shows how the Deam's model described above may be used to show relation between acoustic sound measured by a microphone in the range of 0-15kHz and the feed rate of the head. Abelan-Nebot et al. reviewed machining monitoring systems based on artificial intelligence [9], including issues like sensor systems applied, signal processing techniques, and the most frequently used

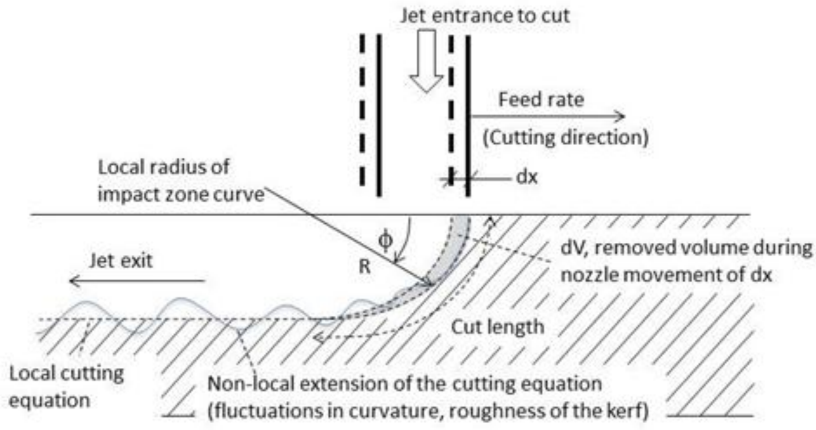

Fig. 4. Outline of local and non-local AWJ process model [4]

descriptors (features). As they point out, there is an extensive use of acoustic emission in process monitoring, but the applications are mainly focused on diagnosis of cutting-tool wear, and breakage detection. Regarding feature selection, majority of the applications relied on the RMS value of AE signal, and AE signal power in specific frequency bands. Other features used are burst rate (number of times the RMS signal exceeds pre-set thresholds per unit of time), burst width, and ARMA coefficients of RMS. Teti et al. in an extensive review of monitoring strategies of machining operations [21] found that AE can detect most of the phenomena in machining, and except the features stated above, proposes also AE signal skewness and kurtosis.

3. STUDY OF APPLICABILITY OF AE-SIGNAL TO MONITORING UNDER AND OVER ABRASION DURING THE AWJ PROCESS

The signal analysis presented below shows the preliminary study of applicability of acoustic emission signal to monitor the AWJ process with focus on predicting of material removal rate and process stability (smoothness). The selected discriminants for analysis was signal RMS power, mean, standard deviation, skewness and kurtosis. Principal component analysis was used to investigate if there is any component in the RMS signal that would give better discriminant allowing discovery of change in AWJ process state. The measured AE signal is presumed to be a sum of a causal, deterministic part and a stochastic noise. This noise contains influence from variables not specified in the model, errors due to assumptions in the modelling and errors of measurement variables.

3.1. ARRANGMENT OF THE EXPERIMENT

The arrangement for the experiment described below is shown in Fig. 1. Jet incidence angle was perpendicular to the workpiece. The workpiece material was titanium Ti6Al4V, abrasive material Australian Garnet mesh #80 (average diameter 180 microns). The AE sensor of type Kistler 8152 mounted by a screw to the workpiece, piezo-coupler 5125, high-pass filter 50kHz, and the sampling frequency 2.5MHz.

The study was conducted for three levels of three process parameters – feed rate, abrasive flow and pressure. The abraded volumes during machining with each combination of the process parameters were measured using confocal scanning microscope and aligned with the AE signal recorded during the machining, as in Fig. 5 below.

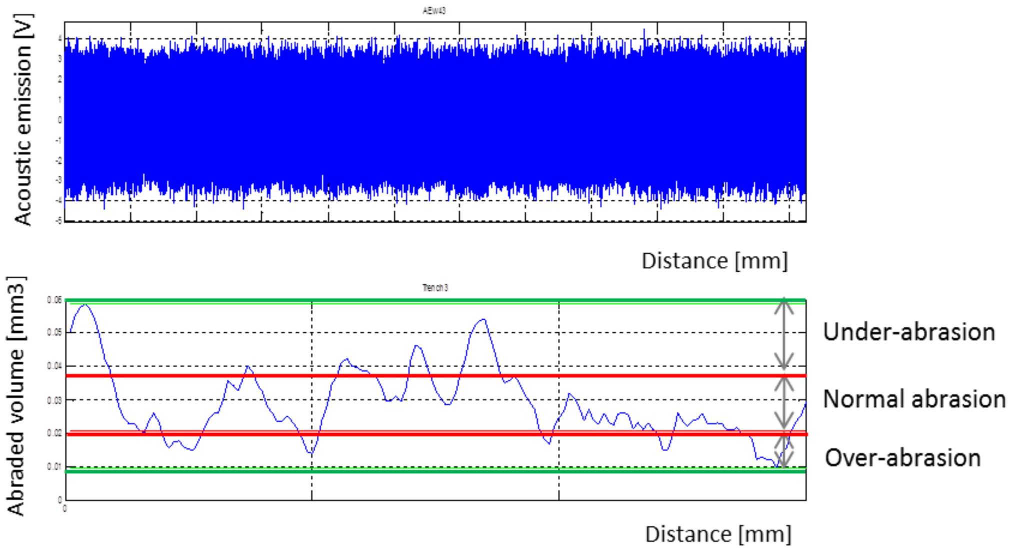

Fig. 5. Aligning recorded acoustic emission with abraded volume for selection of AE signal frames coming from different process states (under-abrasion, normal abrasion and over-abrasion

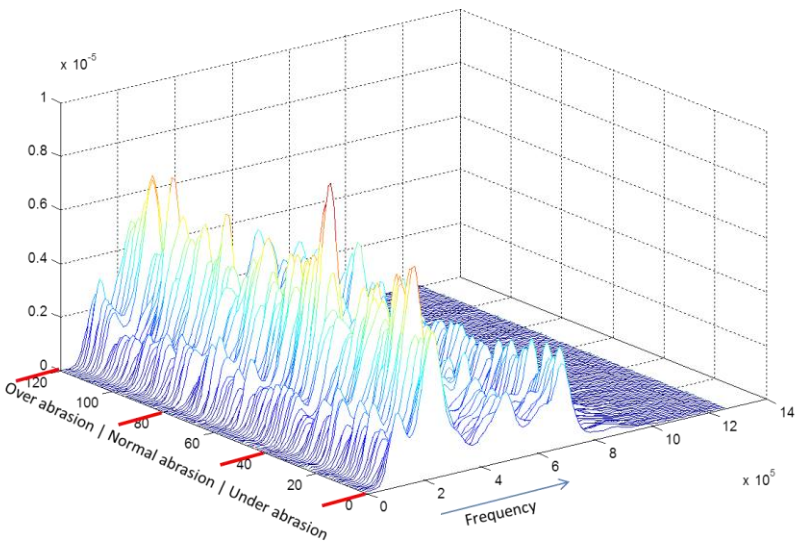

Fig. 6. PSD of AE frames in the different process states

The acoustic emission signal was divided into frames of 1 millisecond each. This corresponds to 2500 samples long frames. For each process state (under-, normal- and over abrasion) 40 such frames was selected. Each cluster of data with 2500x40 samples originated from the three process states. Fig. 6 shows power spectrum density of these data clusters.

The frequency for maximum power spectrum density value is constant for all frames, and process states, which allows the assumption that the system between the cutting point and the AE sensor is at resonance. There is not any correlation of any of the peak frequencies visible in the Fig. 6 to the mean frequency of the abrasive particles hitting the workpiece during the process. E.g. for mesh #80 20g/min it would be around 47kHz – a frequency that is no appearing in the spectrum (the first peak frequency visible in Fig. 6 is 108kHz).

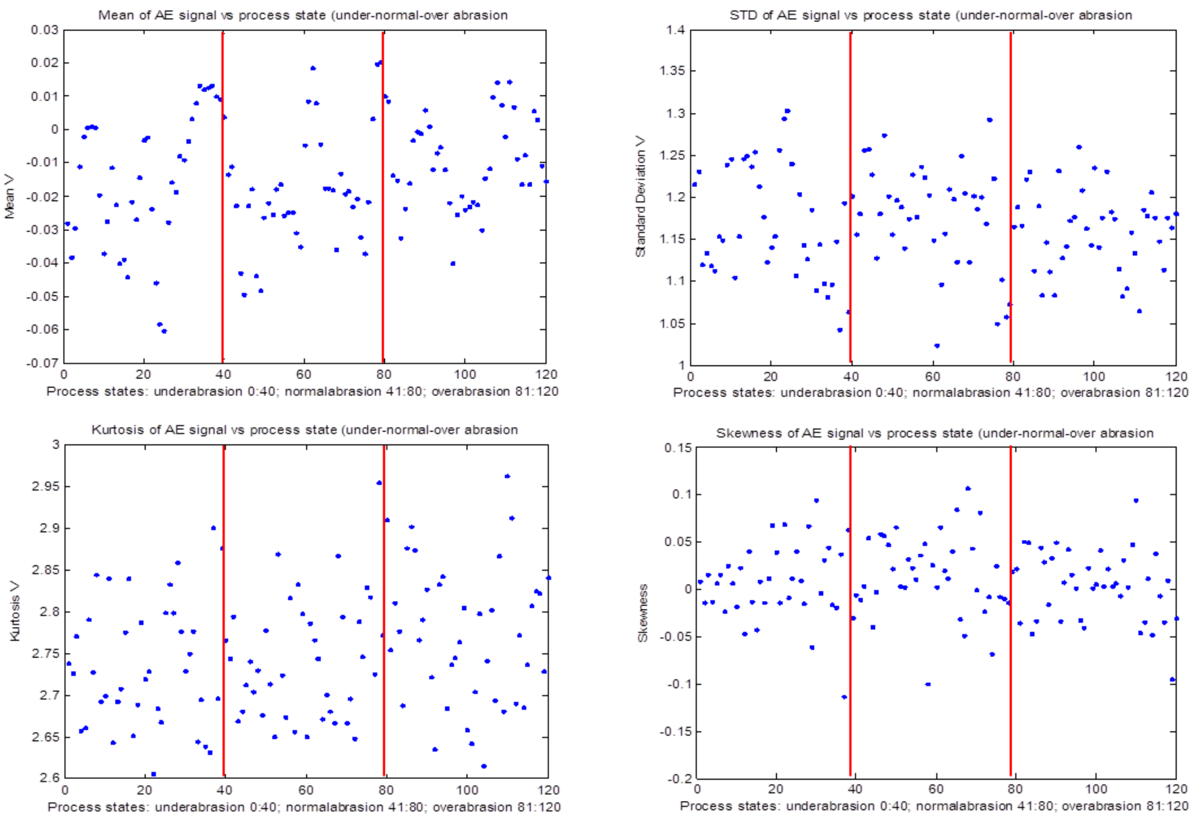

Fig. 7. Scatter plots of features vs process states. No any significant difference between the three states

This may be explained so, that the abrasive particles randomly hitting the workpiece excite the structure and force it to oscillate with its resonance frequency. This hypothesis however should be confirmed in further research.

The next step was to compute the discriminants (features) and check their discrimination ability between the three process states. As mentioned above, the investigated signal parameters were: signal RMS power, mean, standard deviation, kurtosis and skewness. None of these features showed any significant ability to represent discrimination between the process states. The results are illustrated in Figs 7 and 8. This analysis was repeated for all the combinations of process parameters (abrasive flow, pressure and feed rate) with the same result.

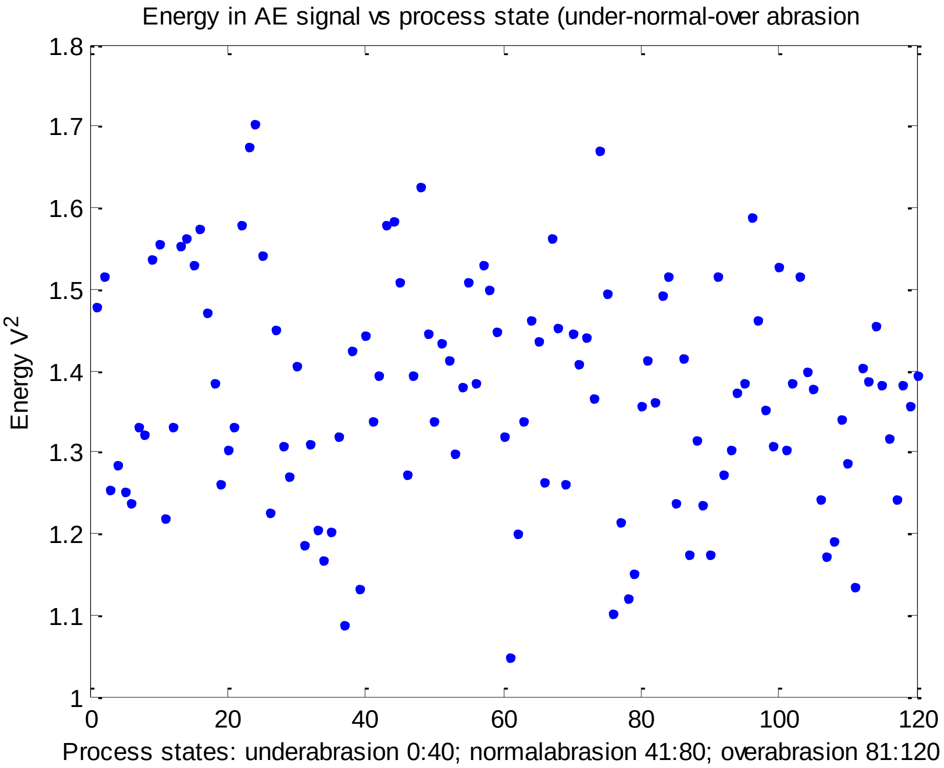

Fig. 8. Scatter plot of signal energy vs process states (under, normal and over abrasion)

The RMS power of AE signal was further analyzed using 7 principal components to check if there is any part of the signal energy that might be used as the discriminant. The signal reconstructed into 2 components PC1+PC2 and the REST is shown in Fig. 9. As it can be inferred from this picture, there are some differences between the process states, but ANOVA analysis showed that these differences are not significant. ANOVA – Analysis of variance – statistical models used for exploratory data analysis. Here used for comparison of groups of data (variance among/variance within) using F-test. The null hypothesis H0 was formulated so that the means between samples coming from the three process states are equal. If the hypothesis could be rejected, the PC1+PC2 components of RMS power would be significantly good discriminators. The performed ANOVA was organized as 3 columns and 40 rows, which gives for significance level 0.05 a critical F statistics = 3.074. The experiment returned F=2.16 for PCs and 0.033 for the rests. The experiments were repeated for 8 different combinations of AWJ process parameters, but in every one of the tests the null hypothesis couldn't be rejected.

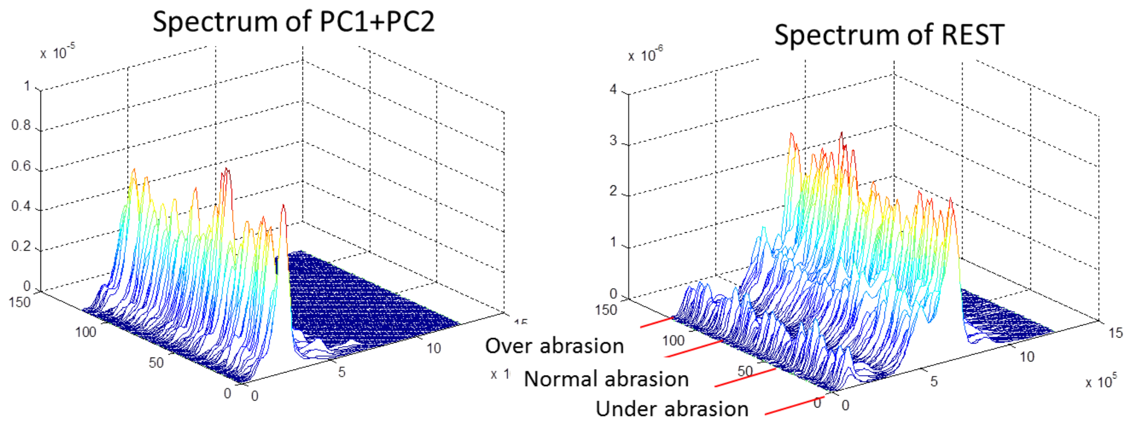

Fig. 9. PCA decomposition. The spectrum of principal components 1&2 (the left picture) and spectrum of the rest (the picture to the right) for the different process states

4. CONCLUSIONS

AWJ process is a new promising technology with many advantages and new applications, but further development requires new strategies for on-line process control of material removal rate and surface roughness. Therefore it is necessary to find process signals allowing discrimination of under and over erosion. In this report the work done on detailed evaluation of applicability of acoustic emission for this purpose is described. It is proved that the usual signal descriptors like mean, standard deviation, skewness, and kurtosis applied to AE signal do not allow to significantly distinguishing between over and under abrasion in AWJ. Also RMS power (or energy) of the AE signal and other features derived from it, including energy divided into different frequency bands as well as their combination doesn't allow for such discrimination. The AE signal energy divided into different principal components configuration without identify significant discrimination is also taken into consideration. Further research is required to find other monitoring methods and other process parameters to follow to improve the AWJ process.

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