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Diagnostic of peripheral longitudinal grinding by using acoustic emission signal

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A B S T R A C T

Grinding burn is one of the well-known problems in grinding processes. The phenomenon of burns causes permanent damage to the ground surface. Therefore, there is a need of monitoring the grinding processes in order to prevent surface damage of a workpiece. This paper presents a method of diagnosing grinding wheel wear with the use of acoustic emission signal generated during grinding. The method aims to detect the occurrence of burn in the surface layer of ground workpieces, and, thus, to replace costly and troublesome surface layer control methods performed after grinding. Experimental research of the grinding process together with the control of surface layer condition was conducted by means of the nital etching method. A band analysis of acoustic emission signal was completed and the influence of the grinding burns phenomenon on the signal amplitude in the range of low frequencies was presented. A boundary value of the *AE* describing the appearance of grinding burns was determined. Moreover, *RMS* value of acoustic emission signal was analysed, and the influence of grinding wheel wear on the signal variations was determined. A new parameter was proposed in order to determine the end of grinding wheel life-time. A boundary value of this *AE* parameter, which indicates the excessive wear of grinding wheel was determined.

A R T I C L E   I N F O

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1. Introduction

Grinding is classified as after-machining and, therefore, it is usually the last step of a technological process. Therefore, grinding and its result determine final parameters of the manufactured parts, which have a direct influence on their operational properties [1]. A very important aspect is ensuring the correct grinding process, namely acquiring the assumed quality parameters of the manufactured products, which include, among others, the condition of the surface layer after machining [2]. Currently, in industrial production the control of surface layer damage of the ground surfaces is done by means of many control methods, often very time-consuming or harmful for the natural environment [3, 4]. Additionally, the use of such methods as fluorescent, magnetic or nital etching ones requires high qualifications from the employees. These measurements are done after machining, thus, approving or rejecting the results of machining.

One type of surface layer damage that completely excludes a workpiece from usage are grinding burns. The term grinding burn refers usually to the altered structure of the ground surface layer of a workpiece, generated in a result of external, thermal influence of contact area of a grinding wheel with a workpiece [5-7]. Irrespectively from the kind of the resultant grinding

burn it negatively influences usage properties of the external layer, causing first and foremost lowering of the fatigue strength. The grinding burns should be detected during the grinding process so as not to accept a thermally damaged product to usage [8].
Performing control during the grinding process enables correction of its parameters and possible prevention of defects during grinding [9, 10]. Therefore, the search for such control methods is an extremely important task [11, 12]. In many papers, an attempt was made to supervise the machining process (the surface layer), that comprised in the measurement and proper analysis of acoustic emission signal (*AE*) generated during grinding [13-17]. Much experimental research was done in the area of controlling the generation of grinding burns during the grinding process, but in none of the studies comprehensive solution to the problem was presented.

An *AE* signal was subjected to various processing methods in order to isolate its parameters that would indicate its relation to the burns. In the last years, a lot of research of the acoustic emission in the grinding was made. For example Dotto, Aguiar and others developed a method for grinding burns detection with the application of acoustic emission and spindle motor power as signals [5, 6], and the efficiency of this method amounted to 82 %. In 2006 Dotto, Aguiar, Serni and Bianchi presented a method for detecting grinding burns that was based on detailed analysis of *AE* static parameters in categories of time and frequency [15], such as: effective *RMS* value, skewness, kurtosis, autocorrelation as well as *CFAR* parameters (*Constant False Alarm Rate*), *MVD* (*Mean Value Dispersion Statistic*) and *ROP* (*Ratio of Power*). Similar studies were done by Wang, Willett, Aguiar and Webster. They came to similar conclusions, but they, however, chose *CFAR* and *MVD* parameters and the ones best correlating with grinding burns. Additionally, they proposed an artificial neural network as the tool for assessing grinding burn occurrence [18]. Qiang Liu, Xun Chen and Nabil Gindy, on the other hand, did studies in which analysis was done with regard to signal distribution in the category of time [19, 20]. Jae-Seob Kwak and Ji-Bok Song performed studies of shafts grinding process with the registration of acoustic emission signal [21] and proposed recording *AE* signal parameters, such as: standard deviation, *RMS* peak value, *FFT* peak value and exceeding the threshold value. These parameters were assumed as input values to the neural network.

Analysing the existing works it should be stated that whereas a burn is distinguished by an increase in the amplitude of the *AE* signal in the range of selected frequencies [18, 22-25]. Up to now, however, the problem of on-line detection of occurring grinding burns has not been comprehensively solved, and the acquired results were often contradictory.

2. Materials and methods

2.1 Experimental details

The test stand, that was created to conduct experimental studies, was built on the basis of the Geibel&Hotz FS 640Z CNC grinder, which can be seen in Fig. 1, together with test equipment.

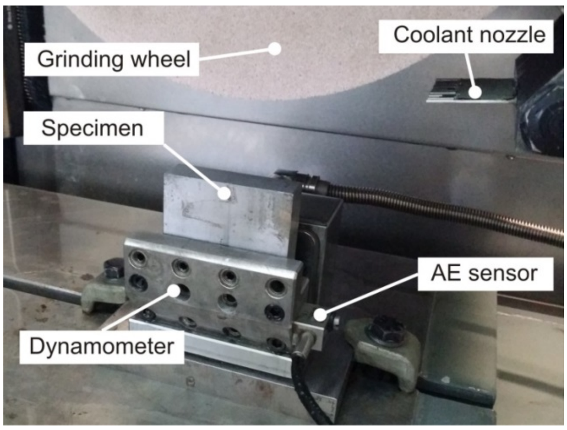

Fig. 1 The view of the test stand

The grinder was equipped with the Kistler acoustic emission measurement system, type 8152B2, with charge amplifier and *RMS* converter, type 5125B1. In the conducted research the value of acoustic emission signal amplitude was registered. It was measured by the *AE* sensor and filtered by a band-pass filter that formed a part of the 5125B1 converter of the Kistler company, and then it was recorded by means of a 12-bit A/D Acquitek measurement card, with sampling frequency of 2 MHz (the sampling frequency was selected with consideration of Nyquist criterion of sensor operation frequency and the range of filtering). All the measurement data were recorded in computer memory in the binary form, and then the data were converted in the MATLAB programme to the form that enabled their further processing and analysis.

Samples the size of 100 × 50 × 15 mm, made of 20MnCr5 steel and subjected to case hardening were ground. The material hardness amounted to 57 HRC. The machining process was performed by a fused alumina grinding wheel of vitrified bond with 4 % solution of semisynthetic coolant. All the samples were initially ground with reduced grinding parameters in order to ensure constant value of ground surface layer cross-section. Then, every sample was one-pass ground and subjected to the process of nital etching in order to identify grinding burns. Detailed test conditions are presented in Table 1.

The initial test was performed and on its basis grinding wheel lifetime was approximately defined, which amounted to V_w = 960 mm^3 for the considered conditions. It means that after 64 passes of the grinding wheel the first grinding burn occurred. On the basis of this study, 35 research samples were prepared, which provided the opportunity to make 70 grinding tests in the period of grinding wheel lifetime. Each sample was ground on both sides.

Table 1 Test conditions

Technological parameters		
Parameter	Symbol	Value
Grinding velocity	v_s	30 m/s
Workpiece length	l_D	100 mm
Workpiece width	b_D	15 mm
Grinding infeed	a_e	0.01 mm
Grinding feed	v_w	2000 mm/min

2.2 Research methodology

Grinding burns develop due to excessive temperature in the grinding zone. Additionally, it is assumed that the amount of heat generated during the grinding process is proportional to the volume of material removed by the grinding wheel, in a given contact surface of a grinding wheel with a workpiece in a time unit [14]. Such an assumption implies that the density distribution of grinding power on the contact surface of a grinding wheel with a workpiece is connected to the size of a ground layer. Additionally, based on a presented relationship it can be stated, that the amount of heat stream in time also depends on the tangential component of the grinding force:

$$q_t = \frac{F_t v_s R}{A_k} \tag{1}$$

where: R – coefficient determining the amount of heat getting into the workpiece, F_t – tangential component of the grinding forces, v_s – grinding speed, A_k – cross section of the ground layer.

In the presented equation the quantities that may change values are the cross sectional area of the ground surface A_k as well as the tangential component of grinding force F_t. The cross-sectional area A_k may undergo uncontrolled changes due to object deformation after heat or chemical-heat treatment. The changes (increase) of force F_t are usually caused by progressive wear of an abrasive wheel. As a result of a wheel blunting, the increase of stress between a grinding wheel and a machined object occurs, as well as the increase of the amount of friction and decrease of machining. This is subsequently followed by the increase of power and grinding forces, and in consequence, generation of an excessive amount of heat in the grinding zone (thermal damage of the ground surface) [26].

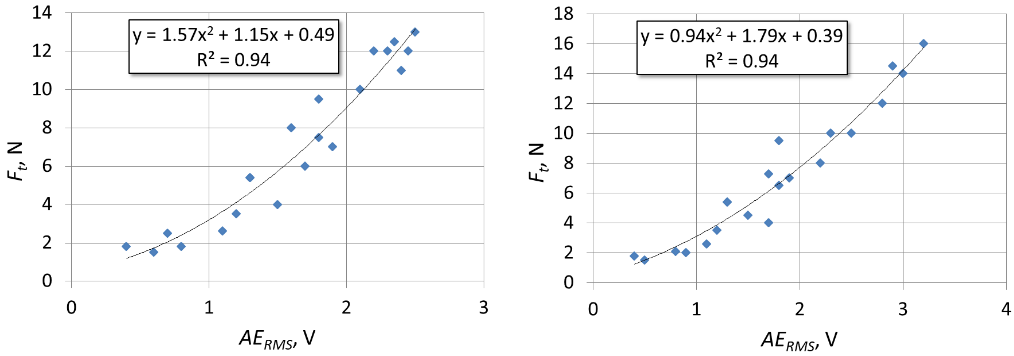

Fig. 2 Correlation of F_t and AE_{RMS} signals in the beginning (left) and in the end (right) of grinding wheel lifecycle

In order to control the grinding process by means of the *AE* signal and considering the aforementioned relationship it was necessary to determine the correlation ratio of AE_{RMS} and F_t. In order to enable replacement of force signal with the signal of acoustic emission, experimental studies were performed to study the functional relationship between these signals. The studies were conducted during the period of grinding wheel lifecycle in order to determine the type of changes of the correlation coefficient and functional relationship. The Fig. 2 presents correlation F_t and *AE* signals in the grinding wheel lifetime.

The presented research results of correlation between F_t and AE_{RMS} signals imply, that in the period of grinding wheel lifecycle, the signals of tangential force and the effective value of acoustic emission are characterised by high correlation ratio $R^2 > 0.9$. It was furthermore observed, that in the grinding wheel lifecycle the functional relationship between the studied signals also undergoes a change. It may be explained by the fact that the level of *AE* signal has an influence on many factors and phenomena taking place in the machining zone, which have an impact on the abrasive wheel wear [16]. It was also observed that the acoustic emission signal in the range of small machining forces is characterised by greater value sensitivity than tangential force. The general relationship of signals $F_t = f(AE_{RMS})^2$ confirms that. Due to the high value of the coefficient of correlation between the effective value of AE signal and the tangential force, it was assumed that the AE_{RMS} signal would be useful in controlling the grinding process.

3. Results and discussion

3.1 Analysis of the *AE* signal

On the basis of the bibliographical research one may conclude, that in grinding burns diagnostics, the spectral analysis of acoustic emission signal may also be useful. A raw *AE* signal, however, must be subjected to complex processing process in order to extract signal features or parameters that have a relationship with the occurrence of grinding burns. Fig. 3 presents the applied algorithm of *AE* processing.

The data for analysis were acquired from a measurement card in a form of files in binary format, which were transformed in order to acquire one result matrix for all measurements. The measurement was done 20 times in each abrasive wheel pass, once in 5 mm.

Then, just before the transition to the frequency range, signal windowing was performed, applying for this purpose the Hamming window. It enabled to avoid signal deformations by the subsequent Fourier transform *(FFT)*. From such prepared data, a frequency spectrum was defined by means of the *FFT* transform. Because the acquired distribution is noisy it is necessary to perform data smoothing (filtering). A filter that gives small approximation error is the Savitzky and Golay filter that functions on the basis of smoothing data with an orthogonal polynomial. Filtration parameters were selected in such a manner as to acquire maximal reduction of random errors and to minimize the introduction of systematic errors. On the basis of bibliographical data, the values of filtering parameters were chosen: degree of an approximating polynomial $j = 3$ and the width of averaging window 201.

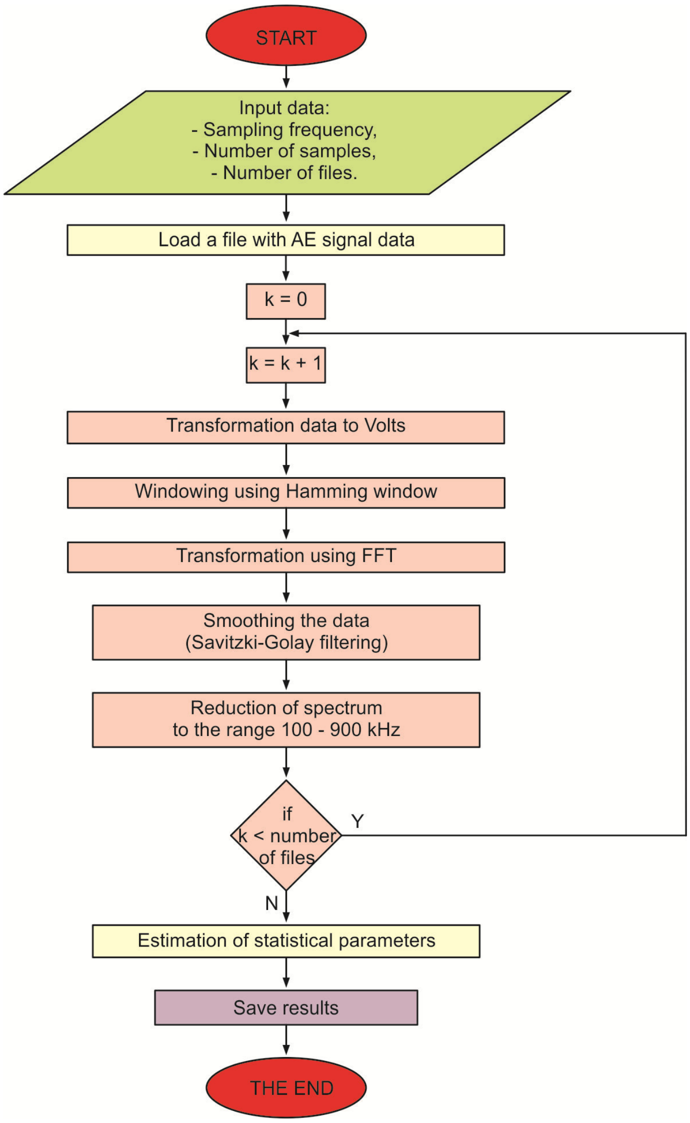

Fig. 3 Algorithm of the *AE* signal processing

The spectral distribution of the *AE* signal filtered this way was subjected to normalization, in order to bring all the frequency spectrums developing in subsequent grinding passes to one level. Each frequency spectrum was normalised by its average value. This method of amplitude spectrum normalization was applied so as to make the values of signal amplitudes independent from uncontrolled and unpredictable changes of the cross-sectional area of the machined layer, which may occur in production, and are a result of workpiece deformations generated in heat treatment. Due to the fact that the *AE* signal was hardware filtered in the range of 100-900 kHz, the spectrum from beyond that range was not taken into consideration. The last stage was the record of all the spectrums to one cumulative matrix. The data processed this way were subjected to further analysis.

During grinding of first samples, the grinding process proceeded correctly and in the test of nital etching no occurrence of grinding burns was observed. Fig. 4(a) shows an exemplary distribution of *AE* spectrums for a signal from one selected grinding pass, in which no thermal damage of the ground surface was observed. The presented spectrums imply, that in the range of all the signal samples no significant changes in the *AE* spectrum occur. Additionally, in fig 2a it can be observed that the *AE* signal has the greatest amplitude in low frequencies, up to 600 Hz, where two ranges of increased levels can be distinguished: 100-300 kHz and 350-550 kHz. In all the cases in which no grinding burns were observed, the signal spectrum was similar.

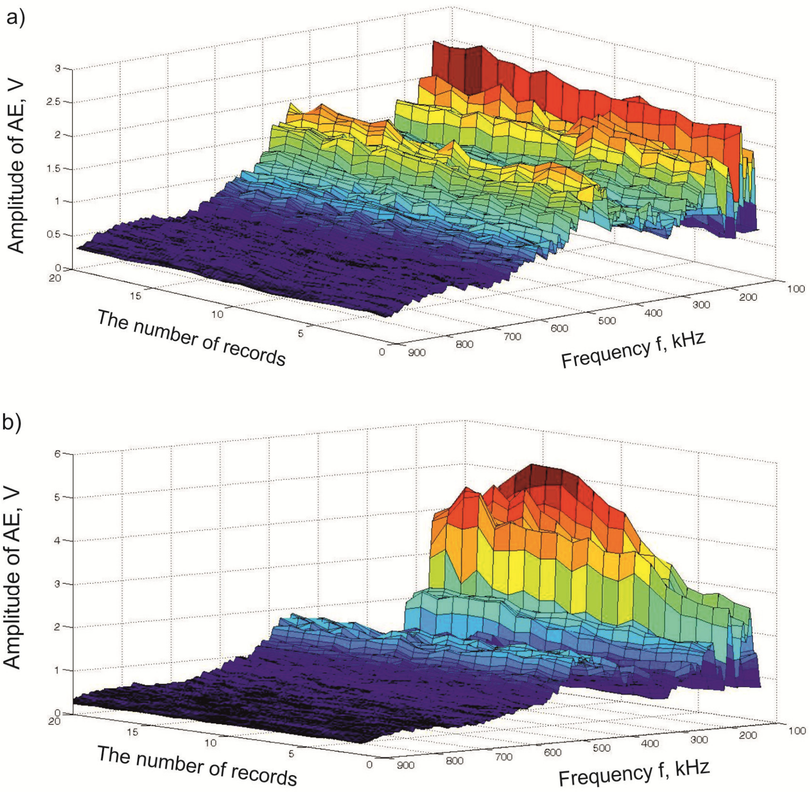

Fig. 4 The *AE* signal spectrum: a) without burns, b) with a visible grinding burn

By the end of the grinding wheel lifetime, the grinding burns started to occur. The first grinding burn was observed in the form of material tempering in the surface layer. The grinding burn was detected at the end of the sample, in the range from 70 to 100 mm of the grinding pass (sample length). Fig. 4(b) presents spectral distribution recorded while grinding the sample, together with a visible increase of signal amplitude in low frequencies, beginning from the 8-th spectrum. Comparing the spectral distribution in Fig. 4(a) with the distribution in Fig. 4(b) one can observe a significant growth of signal amplitude in the range of 100-200 kHz, while in the remaining part of the spectrum the increase is unnoticeable. This increase is observed for all spectral distributions generated from a signal recorded in the cases in which a grinding burn occurred.

The distributions of the *AE* signal recorded during further grinding of samples and the occurrence of subsequent thermal damage, such as tempering or secondary hardening, imply that irrespectively of the kind of the grinding burn, the same type of change of the *AE* signal spectrum occurs. A significant increase in the amplitude of the *AE* signal is observed in the range of frequencies of 100-200 kHz. The same changes in frequency spectrum were observed also in the case of the occurrence of grinding burns, which were acquired by increasing the infeed to the value of a_e = 0.2 mm. Thermal damage was not a result of the grinding wheel wear, but of the increased machining allowance. It is confirmed by the fact, that the increase of amplitude in low frequencies has a relationship with the occurrence of grinding burns, irrespectively of their cause.

In all cases of the grinding burn occurrence, an increase of energy in low frequencies was observed, but the maximal amplitudes were observed for different frequencies. Due to this fact, the frequency spectrum was analysed by bands, every 100 kHz, analysing the maximal amplitudes. Fig. 5 compiles maximal values of amplitudes in particular bands of the *AE* signal spectrums, recorded during grinding tests, in which a grinding burn occurred, and in these in which no grinding burn was observed.

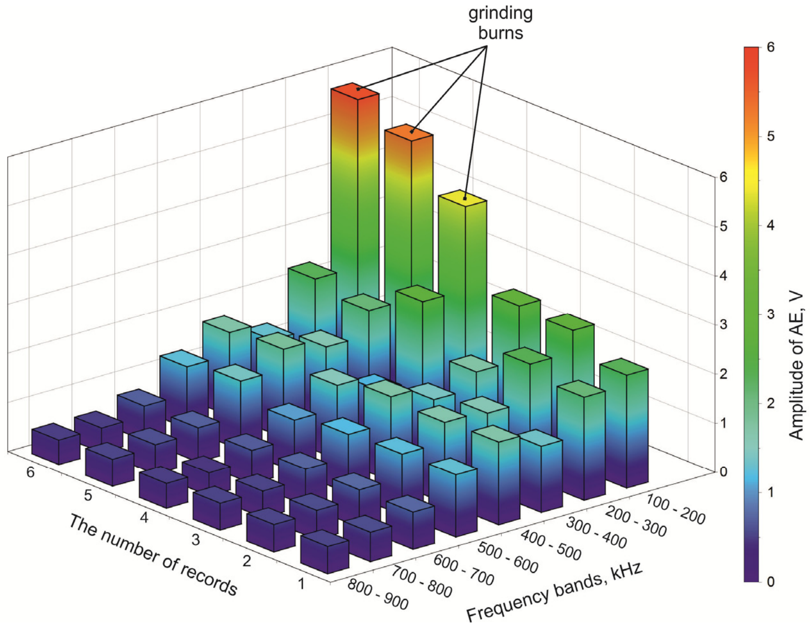

Fig. 5 Maximal values of the *AE* signal amplitudes in bands, every 100 kHz

It may be concluded from the presented research results of the changes of the *AE* signal spectrum in particular frequency bands, that the best criterion for the assessment of grinding burns occurrence is the value of the maximal amplitude of the signal in the 100-200 kHz band, because the amplitude of *AE* signal in the case of grinding burns occurrence is almost two-fold higher than in the process without visible burns.

In order to specify the criterion of grinding burns occurrence, a statistical analysis of computed maximal values of amplitudes *AE* was conducted in the band of 100-200 kHz. 30 maximal values of the *AE* amplitudes were chosen at random, for the cases in which grinding burns occurred, as well as 30 amplitudes for the cases without burns. For each group confidence interval was computed, assuming the significance level $\alpha = 0.05$. Due to the fact that confidence intervals do not overlap, an unambiguous criterion for the occurrence of grinding burns was proposed in the form of the P_p parameter, that is defined by the relation:

$$P_p > \frac{\mu_{g\,min} - \mu_{d\,max}}{2} \tag{2}$$

where: $\mu_{g\,min}$ – the bottom value of the confidence interval of the *AE* signal amplitudes for the occurrence of grinding burns, $\mu_{d\,max}$ – the top value of the confidence interval of the *AE* signal amplitudes without the occurrence of grinding burns.

It can be assumed, that for the case under study, when $P_p > 3.5$ then a grinding burn occurs with the probability of $p = 0.95$.

3.2 The AE_{RMS} analysis

The effective value AE_{RMS} that was hardware generated by the *RMS* converter, type 5125B1, had been recorded. Then, signal values were subjected to normalization in order to acquire average values of the AE_{RMS} signal with reference to the cross-sectional area of the machined layer A_k. This procedure was performed in order to eliminate the influence of uncontrolled changes of machining allowance, resulting e.g. from object deformation during heat treatment, on the *AE* signal. For the AE'_{RMS} normalised signal that was acquired in the stated above procedure the average value for one grinding pass was computed. The recorded waveforms imply that the average value AE'_{RMS} changes in the period of grinding wheel lifetime and has a rising tendency. Fig. 6 shows changes of the processed signal value AE'_{RMS} for all grinding tests in the period of grinding wheel lifetime.

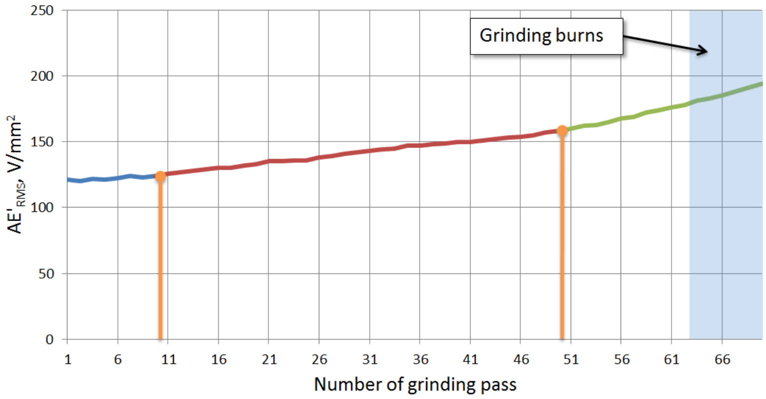

Fig. 6 Change of the AE'_{RMS} signal in the period of grinding wheel lifetime

The presented waveform implies that the AE'_{RMS} signal is correlated with the progressive wear of the grinding wheel in the period of its lifetime. Analogically to the correlation studies of F_t and AE_{RMS} signals one may distinguish three stages of grinding wheel utilization in the period of its lifetime. The first stage is connected to a grinding wheel active surface forming and appears in the beginning of the lifetime. It may be observed that the AE'_{RMS} signal presents slightly rising tendency, significantly smaller than the one occurring during further period of grinding wheel utilization and is characterised by relatively great dispersion of values. It can be explained by the phenomenon of chipping of abrasive grains that were not removed in the dressing process, and their connection with the bond. Together with crumbling of the abrasive grain and blunting their edges, the AE'_{RMS} stabilizes and starts to rise. Then, the second stage of grinding wheel utilization takes place, in which glazing of abrasive grains and partial pore-filling dominates. It can be observed, that at this stage the AE'_{RMS} signal slightly rises, which is probably caused by the progressive wear of the grinding wheel. In the end of the lifetime, the third stage occurs, in which a significant increase in the value of the AE'_{RMS} signal can be observed. The abrasive wheel is glazed and has filled pores, resulting in losing the machining properties. The third stage of the grinding wheel utilization is the end of the lifetime of a grinding wheel.

By the end of the grinding wheel lifetime, the grinding burns occur. The area of grinding burns is marked in blue in Fig. 6. However, on the basis of the signal value changes AE'_{RMS} it is not possible to specify the moment, when first burns occur. Nonetheless, it can be observed, that by the end of the grinding wheel lifetime period, the AE'_{RMS} signal shows a greater increasing tendency in comparison to the middle period of its utilization.

Taking into consideration the nature of the AE'_{RMS} signal changes, the following method for assessing the end of the grinding wheel lifetime is presented. Due to the fact, that the AE'_{RMS} signal shows a linear increase with the progressive wear of the grinding wheel, it is possible to determine the equation of lines that approximate changes of the AE'_{RMS} signal in particular stages of the grinding wheel utilization (Fig. 7).

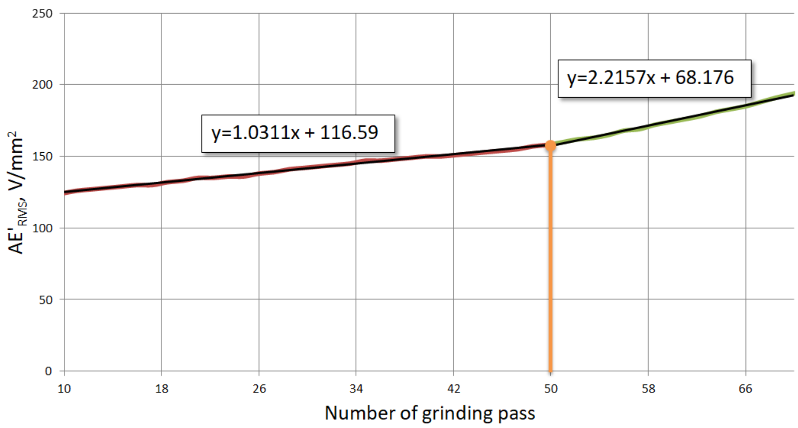

Fig. 7 Approximation of the AE'_{RMS} signal change in the period of the grinding wheel lifetime

In order to control the wear of the grinding wheel in on-line mode and stop the grinding process by the end of the grinding wheel lifetime, a proper criterion, that clearly defines the moment of the end of the grinding process and dressing the abrasive wheel should be selected to avoid the occurrence of grinding burns. Developing the criterion of the end of the grinding wheel lifetime, one should take into consideration the fact, that analysis of the *AE* signals acquired from the insufficient number of grinding passes will cause the criterion instability. However, too high a number of the *AE* signals will cause that the criterion will react too late. A compromise solution was developed by means of the P_g parameter, expressed by the following relationship:

$$P_g = \frac{\frac{1}{3}\sum_{k}^{k-2} AE'_{RMS(k)} - \frac{1}{3}\sum_{k-3}^{k-5} AE'_{RMS(k)}}{3} \tag{3}$$

where: $AE'_{RMS(k)}$ – the average value of the AE'_{RMS} signal for the *k-th* grinding pass. The value of the P_g parameter for the *k-th* grinding pass is obtained from the previous six passes. The difference between average values of signals obtained from grinding passes, k-1 and k-2 as well as k-3, k-4, k-5 is divided by 3; thus the value of the P_g parameter can be compared to the directional coefficient of lines that approximate the change of the AE'_{RMS} signal in time.

Due to the fact, that by the end of the grinding wheel lifetime the directional coefficient increases over twofold, the following criterion that determines the end of the grinding wheel lifetime was calculated:

$$P_g > \frac{a_1 + a_2}{2} \tag{4}$$

where: a_1 = 1.031, a_2 = 2.216 – directional coefficients of lines. Fig. 8 shows the change of the P_g parameter in the grinding wheel lifetime.

The end of the grinding wheel lifetime occurs when the difference between average values of the AE'_{RMS} signal is higher than the average value of the directional coefficients of lines, which describe the signal change in the period of the grinding wheel lifetime P_g > 1.62. Achieving this value implies, that the grinding process should be stopped. The criterion of the end of the grinding wheel lifetime was met by the 60th grinding pass, before the first occurrence of grinding burns.

The analysis conducted for the AE_{RMS} signal in the grinding wheel lifetime implies, that by applying proper method of processing, the signal and the method of assessing the change of its value, it is possible to define the end of the grinding wheel lifetime in the peripheral longitudinal grinding process even before the first occurrence of grinding burns.

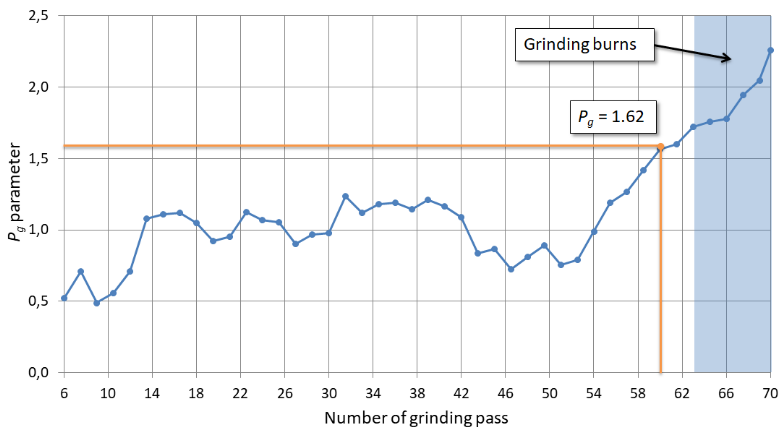

Fig. 8 Change of the P_g parameter in the grinding wheel lifetime

3.3 Diagnostic methodology

In practice, grinding burns usually occur due to two factors:

- Loss of grinding wheel's machinability and reaching the end of its lifetime,
- Uncontrolled local variations of machining layer, generally due to workpiece deformation during heat or chemical-heat treatment.

Due to the existence of two separate sources of grinding burns, developing of two diagnostic methods, that are able to react to grinding burns has been necessary. Thus, a separate spectral analysis of raw *AE* signal as well as its *RMS* value was performed. The analysis allowed to formulate two criteria of grinding process diagnostics (Fig. 9):

- Criterion I, based on measurement and analysis of AE_{RMS}, if parameter $P_g > 1.62$, it means, that a grinding wheel reached the end of its lifetime and grinding process should be stopped in order to avoid grinding burns,
- Criterion II, based on a spectral analysis of *AE* signal, if parameter $P_p > 3.5$, it means, that a grinding burn on a workpiece surface occurred, however, the wear of a grinding wheel had not been the source of a burn.

In Fig. 9 an idea of complex diagnostics system of grinding process based on the measurement and analysis of *AE* signal is presented. It depends on continuous control of the value of two parameters: P_p and P_g. If parameter P_g exceeds established threshold value, it means, that the grinding process should be stopped and the grinding wheel dressed. Continuing the grinding process may lead to grinding burns. Whereas, when parameter P_p exceeds established value, it means that a thermal damage to the workpiece occurred. Application of presented in Fig. 9 diagnostics system allows to have constant control of grinding process as well as prevents grinding burns occurring due to grinding wheel wear.

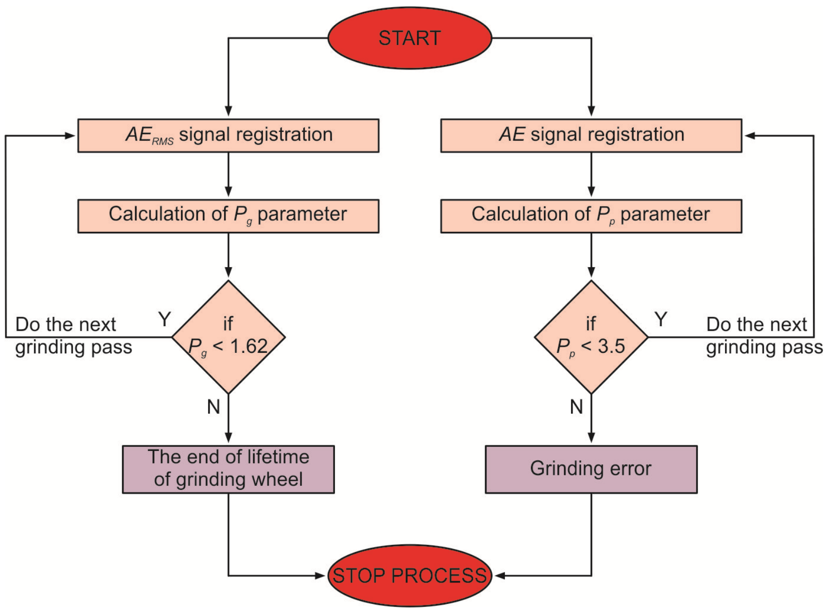

Fig. 9 General operation algorithm of the grinding diagnostics system

4. Conclusion

The above paper discusses a new method for the surface layer control during the peripheral longitudinal grinding, using acoustic emission as the diagnostic signal. The method solves comprehensively the problem of detecting and preventing the occurrence of grinding burns. The two-passes analysis of the acoustic emission signal enables to stop the grinding process before first grinding burns occur, as well as to determine a probable cause of the burns.

The most important scientific accomplishment of the paper is presenting a new, complex method of grinding burns detection and its prevention. In the diagnostic method, two parameters were used: P_p and P_g, for which threshold values were determined, allowing to prevent thermal damage to the ground surface.

The developed method of the grinding process diagnostics is based on measurement, processing and analysis of the *AE* signal. The root mean square of *AE* in a grinding wheel lifetime was analysed. The criterion, that defines the moment of the end of the grinding wheel lifetime and allows to avoid the occurrence of grinding burns was developed. The new parameter P_g had been proposed. When its value exceeds 1.62, the grinding process should be stopped.

Due to the fact, that it is not possible to detect the occurrence of grinding burns by means the AE_{RMS} signal, the *AE* signal was also analysed in terms of frequency, searching for the connection between grinding burns occurrence and the *AE* signal spectral parameters. A suitable band analysis of the acoustic emission signal enables to detect grinding burns irrespectively of their cause. The new method of calculating the parameter P_p was proposed, which may be applied in order to detect thermal damages of grinding surfaces. When $P_p > 3.5$, it indicates that grinding burns will occur during grinding.

The method does not require almost any structural changes to the grinder and the *AE* signal sensors are not very susceptible to external factors. The application of this method requires developing a proper procedure for processing and analysing the *AE* signal in the range of frequency. The analysis is necessary to define signal parameters and to specify the conditions determining the occurrence of thermal damage to the workpiece during the machining process. It should be noted, that the boundary values of the P_p and P_g parameters were determined for the adopted study conditions and for other types of ground material and different abrasive wheel they may assume different values.

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