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SURFACE EVALUATION DURING THE GRINDING PROCESS USING ACOUSTIC EMISSION SIGNAL

The hereby article presents results of experimental tests which prove the possibility of indirect evaluation of the grinded object's quality with the application of monitoring and analysis of selected acoustic emission signal (AE) registered during the machining process. As the grinding process is carried out and the grinding wheel wear progresses, the acoustic emission signal value is shaped adequately to the workpiece surface quality changes. The binding descriptor of changes of roughness profile and material residual stresses is the RMS value of the acoustic emission signal and in particular the statistical features that characterize the distribution of values contained in the signal sample in relation to the average value. The analysis results indicate that the acoustic emission signal is a convenient indicator for evaluation of stresses cumulated in the surface layer of the material and in selected surface geometrical structure parameters.

1. INTRODUCTION

In the machining process, the input mass stream (material) is processed using the provided energy into two output streams: the product and the residual processes. The technical condition, including the level of tool wear and the product quality, can be determined by performing periodical diagnostics. However, evaluation of the object condition and quality in an indirect way is far more favorable. This is achieved through analysis of intensity of various accompanying processes such as thermal radiation, vibrating, acoustic and electromagnetic phenomena.

At present one of the easily measurable residue processes that accompany the grinding process is acoustic emission which is connected with creation of impulses in the form of elastic waves propagated by the machined material and the grinding wheel. In consequence, the signal can be registered both on the side of the tool and the workpiece. The usefulness of analysis of this signal as a tool for controlling the grinding process course in its various aspects was confirmed in numerous research works [3],[4],[7].

The shape and nature of the registered acoustic emission signal depends on a number of factors. In order to obtain reliable information concerning the occurrences in the

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machining zone, certain characteristic AE impulse parameters are selected and examined. Their description in time and in relation to the other external symptoms makes it possible to determine what processes take place in the analyzed source.

As a result, the basic aim of the diagnostic tests, discussed in the article, was relating the machining results, expressed in the residual stress changes, and the workpiece roughness to the symptoms revealed in the AE signal. For this purpose, between the object (workpiece) condition and the output value that describes it, an attempt was made to determine the implication which can be expressed in the following way: if the physical value (selected signal parameters) adopts value A, then the object finds itself in condition B (stress and roughness). The below section contains a description of the research methodology and compares the results of the this conducted tests and analyses.

2. RESEARCH METHODOLOGY

The tests included the process of grinding of flat surfaces of samples made of hardened steel NC10 (60±2) HRC. What was used in the experiments was a peripheral surface grinding machine of Russian production (type OC3, model 3711 – Fig. 1) and a grinding wheel made of quality electrocorundum99A grains and ceramic bond 1-250x32x98-99A60J7V-42m/s (according to PN-ISO 603-4:2001).

The experimental tests were conducted for constant grinding parameters: grinding wheel circumferential speed $v_s = 27,5$m/s, tangential feed speed $v_{ft} = 24$m/min; axialtable feed speed per stroke $f_a = 0,3$mm and grinding wheel working engagement $a_e = 0,03$mm. The grinding procedure was conducted using coolant (5% water-in-oil emulsion, capacity $Q_c = 3\text{dm}^3/\text{min}$).

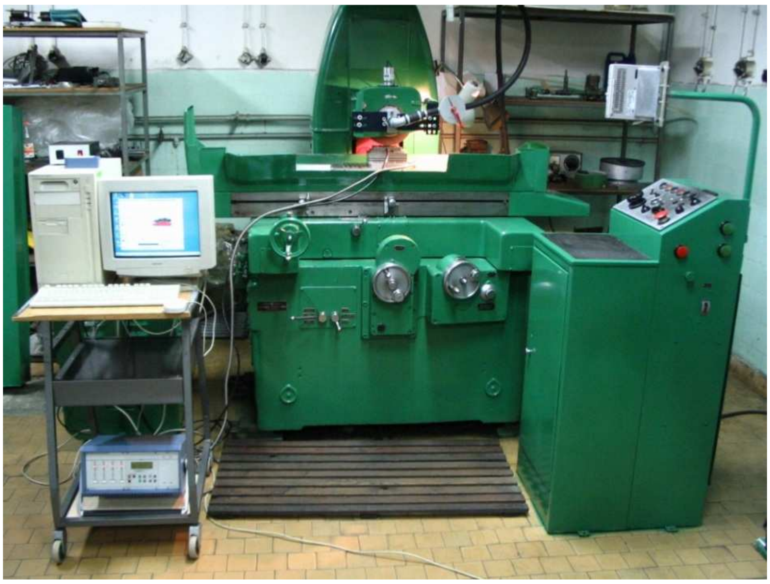

Fig. 1. Experimental setup for monitoring of the surface grinding process (overall view)

The process output variables were recorded using specialistic devices produced by Kistler company (Switzerland). The 8152A2 type sensor and the 5125A type converter were used to measure the acoustic emission signal. The AEsignal was analyzed with the aid of its RMS value using the time constant 0,12ms and filtration passband 0,1–1MHz.

After some volume of material removal, changes in selected workpiece physical parameters as a function of the grinding time were determined: the maximum residual stress in the macrostress scale (stress of the first type) below the surface layer, and the surface geometrical structure parameters. The stress was calculated using the Weissman-Philips method, while the multiparameter surface microstructure analysis was conducted with the aid of the contact method using ME10 profilometer produced by Carl Zeiss Jen (Germany).

3. RESULTS AND DISCUSSION

What should be anticipated as a result of progressive tool wear is an increase of stress in the workpiece surface layer [6]. This results from the constant expansion of the zone of contact between the grinding wheel and the workpiece over subsequent wear stages, which in turn leads to grinding energy and power rise and therefore also temperature increase in the machining zone. The grinding wheel wear is also directly connected with shaping the surface geometric structure (SGS), which includes: roughness, waviness, shape lapses and material defects.

The conducted grinding process was of finishing nature, which means that the analyzed test results should be treated as information on the final exploitative properties of the object. For this reason, being familiar with the dependence between the obtained surface quality, expressed in roughness parameters, and the surface layer stress is an essential element of the diagnostics process. The results of correlative analyses of roughness and stress parameters variability in relation to the registered acoustic emission signal are presented below.

3.1. CHANGES IN SURFACE ROUGHNESS AND SURFACE LAYER STRESS

The surface geometric structure was evaluated using the basic parameters that refer to particular quality features of the product. The amplitude parameters were described with the arithmetic average of Ra roughness profile ordinates. Ra value is used as a privileged parameter of product surface technical characteristics. Its value is assumed by the constructor at the very designing stage. The distance parameters were characterized with the average width of element grooves of the RSm roughness profile. It expresses the frequency of profile rises which are characteristic of surfaces with periodical geometrical structure, obtained as a result of application of feed in processes such as turning, milling and grinding. The root mean square slope of the roughness profile $R\Delta q$ (local slopes of the measured profile), which due to its dependence on the machining conditions can be used in evaluation of the process course – Tab. 1, was taken into consideration out of the mixed parameters.

Table 1. Physical/functional significance of several surface texture parameters [2]

Functional properties	*Ra, Rq*	*Rp, Rpm*	*Rt, Rz*	*Rsk*	*Rku*	*RSm*	*R*Δ*q*
Contact/Contact stiffness	+		++	+	+	++	+
Fatigue strength	+	+	++		+		++
Thermal conductivity	+	++				++	+
Electrical conductivity	+					+	+
Reflexivity			++				++
Friction and Wear	+		++	++	++	+	++
Lubrication	+	+	++	++	+		+
Mechanical sealing	+		++	++			++
Fatigue corrosion	+	+		+		+	+
Assembly tolerances	+		++				+
Note: the two asterisks indicate a pronounced influence.							

Moreover, the material ratio of the roughness profile *Rmr*(*c*) was determined for level $c = 0{,}2\mu m$ (it was assumed that the anticipated working conditions of the examined surface would be characterized by unit pressure). The measurement of this parameter is the most commonly used method of obtaining information on the surface load capacity, i.e. its resistance to pressure [1].

The registered changes of the selected parameters that describe the machined material surface microgeometry, obtained in the discussed test conditions, are presented in Fig. 2. These parameters are presented in the form of average value with the standard deviation for each measurement point.

When analyzing the roughness course expressed in the average arithmetic deviation of the machined material profile ordinates $Ra_{(w)}$, which is most often used in research works and product technical control, it should be assumed that it is characterized by a visible decreasing value in the grinding wheel working time function. Index (w) refers the analyzed parameters to the sample material. The index was used in order to emphasize the fact that the analyzed surface is not the tool surface despite its unquestionable changes over the analyzed working time and its decisive influence on shaping the machined material quality. The grinding wheel dressing procedure exerted decisive influence on the obtained roughness of the grinded surface at the beginning. During the initial resistance wear of the grinding wheel, the grains that were poorly attached to its structure were chipped and simultaneously the average value of the grinding wheel surface roughness increased. The great number of sharp cutting edges resulted in a quick drop of the grinded surface roughness. The remaining part of the observed changeability of the $Ra_{(w)}$ parameter was characterized by systematic roughness drops as a result of blunting of the grains and smearing the grinding wheel intergranular spaces.

The average spacing of local profile slopes $RSm_{(w)}$ is characterized by a distinctive increase and then a sudden drop. Such a nature indicates the occurrence of typical changes in the machining zone over the initial period of the grinding wheels' operation. The fast grain loss as a result of cracking of the bond bridges led to an increase in the spacing between the abrasive grains' apexes. The apexes microchipping on the abrasive wear stage decreased the distances between the profile elements. All of the changes in the grinding wheel surface geometry were reflected in the shape of the machined surface microgeometry.

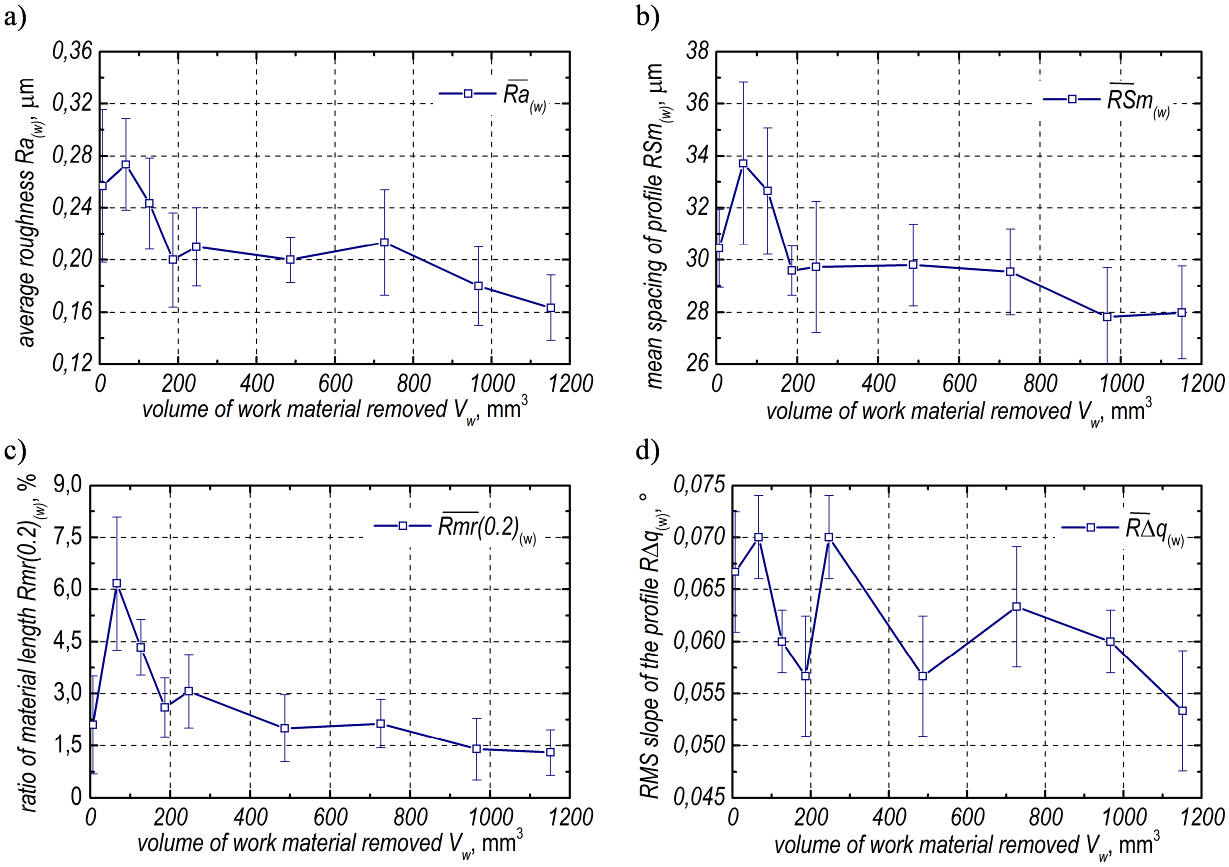

Fig. 2. Changes in the values of selected roughness parameter soft her machined surface over material removal: a) arithmetical average deviation of the roughness profile, b) mean width of the roughness profile elements, c) material ratio of roughness profile, d) root mean square slope of the roughness profile

Values of the load ratio of profile $Rmr(0,2)_{(w)}$ were subject to clear regression in the grinding wheel working time function, which suggests a decrease in the examined surfaces' resistance to abrasion. Application of constant reference level and changes in the grinding wheel microgeometry influenced the observed results. Comparison of the obtained results with the other parameters indicates that the obtained surfaces are characterized by an increasing number of low with constant amount of high sharp apexes.

The distinct drop in the value of roughness profile slope value ($R\Delta q$) in the grinding wheel working time function occurred over the whole analyzed period. This means that the sample surface roughness profiles gradually decreased their unevenness. The local increase of the parameter value suggests the occurrence of the grinding wheel self-sharpening phenomenon. The above symptoms are indicative of typical tool wear sign – at first, the grinding wheel experienced resistance wear and over time the abrasive wear of the grains became the dominant type.

The grinding process parameters and progressive grinding wheel wear had direct influence on the value and type of the accumulated residual stress in the surface layer of the analyzed samples. The stress can be deemed unfavorable as (apart from the subsurface layers up to the depth of 25μm) it was negative stress (+*σ*), which is presented in the below charts (Fig. 3a).

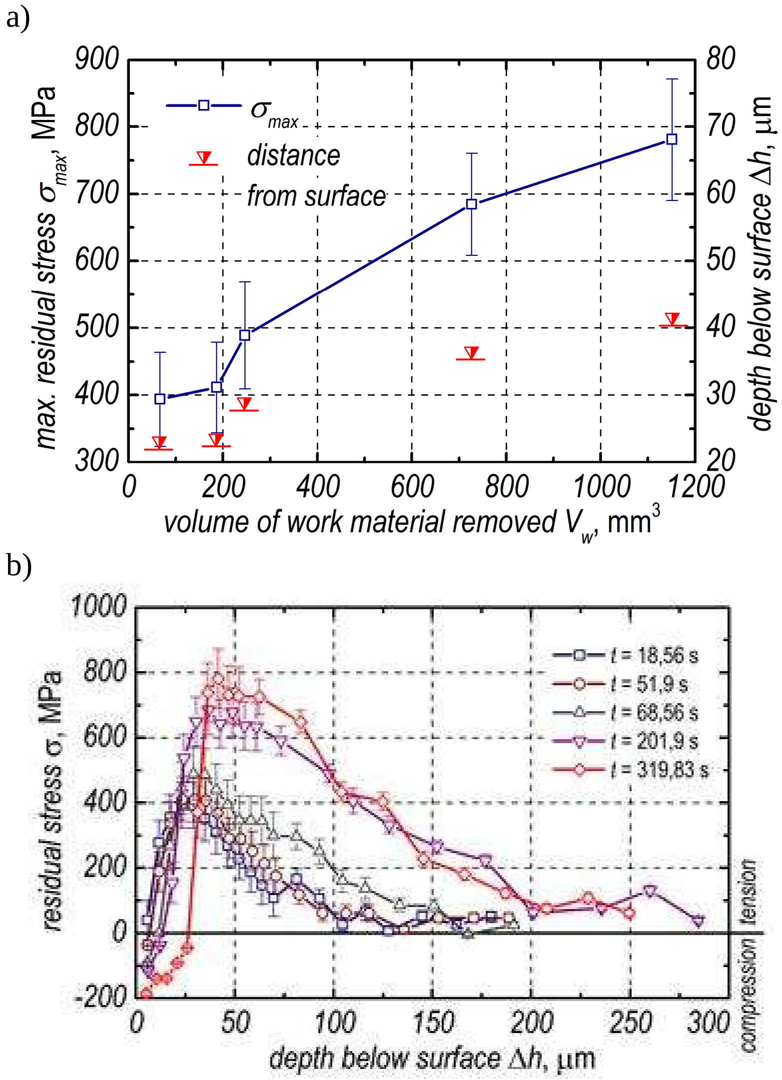

Fig. 3. The distribution of residual stresses of the first kind in grinding surface layers over material removal: a) in function of depth below surface, b) maximal residual stress and depth values

Over the long-lasting grinding process, with the progressive resistance and abrasive wear of the grinding wheels, it may be assumed that changes in the components of force occurred in the grinding zone. As the tests were carried out with constant machining parameters, the values of grinding force components were mostly dependent on the grinding wheel active surface geometrical features, i.e. on the temporary shape and distribution of the abrasive grains apexes. The increase of the abrasive grains' abrasion, i.e. the progressive abrasive wear and the expansion of the grinding zone field, resulted in a force rise in the grinding zone and therefore led to gradually increasing friction of the abrasive grains on the machined surface. Increasing the grinding force components amounted to increasing the grain cutting energy. As the energy was almost completely transformed into heat that penetrated the machined material, the gradient temperature changes cause by the grinding wheel wear exerted significant influence on the physical and chemical changes in the surface layer.

When examining the distribution of stresses accumulated in the surface layer of the objects that underwent machining in the grinding wheel working time function (Fig. 3b), it was unequivocally concluded that the registered highest values (σ_{max}) for subsequent measurement points adopted higher and higher values. At the same time, the $h_{\sigma max}$ values (the highest stress value below the surface) also shifted towards greater depths.

3.2. CHANGES IN THE ACOUSTIC EMISSION SIGNAL

The analysis of the registered acoustic emission changes was based on interpretation of the form processed to the RMS value of the signal (AE_{rms}). In the grinding wheel working time function and therefore also in the work material removal function V_w, the registered AE_{rms} signals and its statistical descriptors were characterized by a distinctive value increase or drop tendency, as illustrated in the below charts (Fig. 4).

The acoustic emission signal cumulates in itself information on all sources of elastic waves registered by the sensor from the grinding zone. The signal form and the descriptor values are therefore dependent on the phenomena that occur on the grinding wheel surface (bond cracks, grain macro- and microchippings, apex abrasions and tearing out of whole grains), the machined material surface(creation and expansion of cracks and microcracks, plastic deformations, phase transitions), on the border of contact between the tool and the material (friction, elastic interactions), and, to some extent, vibrations of the whole shaping machine system [5].The high sensitivity of the method exerts negative influence on the value range in relation to the average in subsequent measurement points. However, the direction of AE signal changes in the work material removal volume is clearly visible.

The root mean square value of the acoustic emission signal (Fig. 4a) increases over the grinding time. This increase is clearly visible in the initial tool operation time, which is usually characterized by resistance wear. Bond cracks and chippings of the abrasive grains require more and more energy over time and therefore they generate impulses of increasing amplitude. When the grinding wheel changes the wear nature, the acoustic emission signal increases slowly and tends to oscillate in relation to the previously achieved level. In this period, in the grinding wheel structure most of the abrasive grains are strongly upheld by the bond bridges, and friction, as well as the related abrasive wear phenomena participate in shaping the AE signal. Analysis of changes of variants from trial s^2, which is the measure of diversity (dispersion force), and the moment of 4th order (which is the measure of kurtosis intensity) for the AE_{rms} signal in the grinding wheel working time function showed a clear value drop only in the initial period – Fig. 4b. It can be therefore concluded that the dispersion or possible signal value kurtosis intensities in relation to the average value, are closely related to the resistance nature of the grinding wheel work.

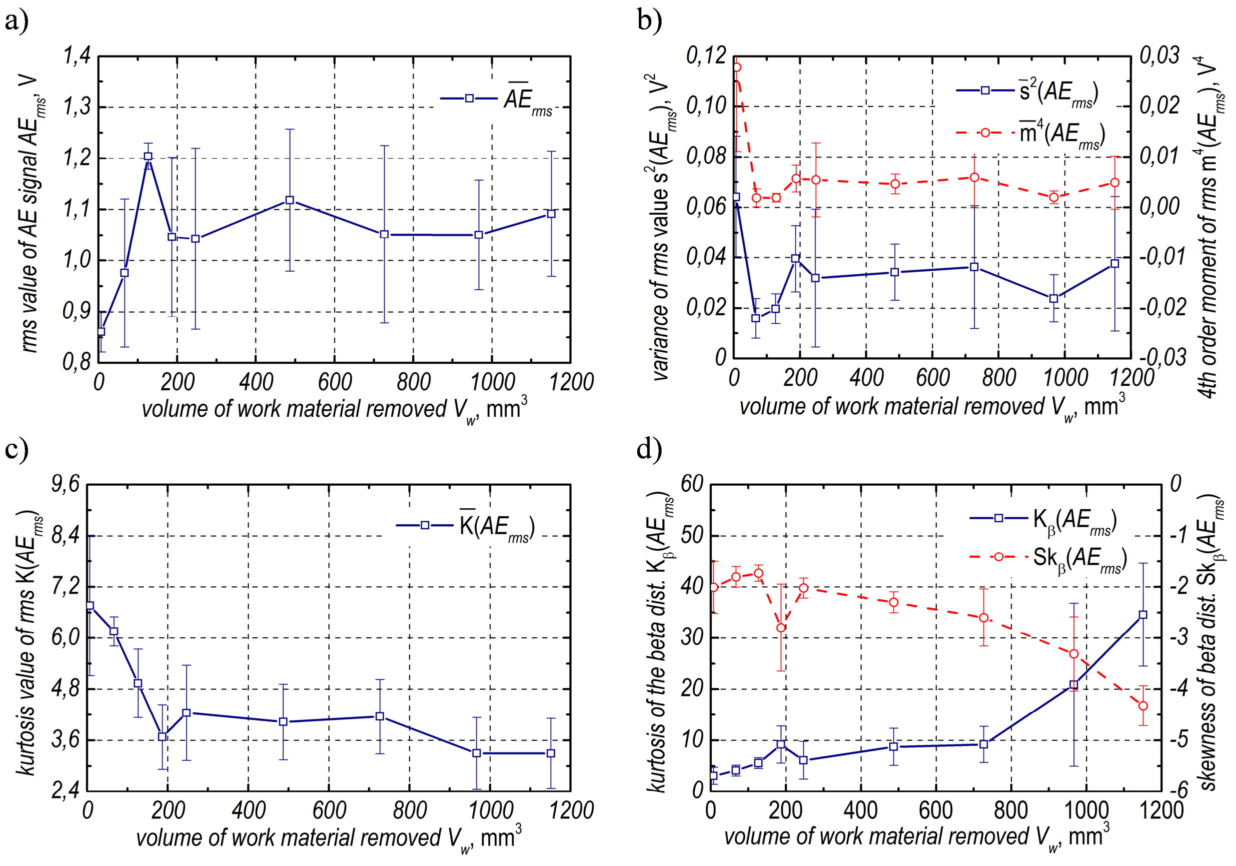

Fig. 4. Changes in theme an values of the selected acoustic emission parameters over material removal: a) root-mean-square (RMS) value of signal, b) variance and 4th order moment of RMS value, c) kurtosis of RMS value, d) beta distribution parameters of RMS value

No vertical asymptote was observed in values of AE_{rms}, $s^2(AE_{rms})$, and $m^4(AE_{rms})$ parameters. The proceedings of these parameters do not have the global extreme at the end of the analyzed grinding wheel working time. A different nature of the value changeability was observed in case of analysis of the flattening and RMS value distribution skewness measures. What was observed in the conducted tests was a consistent drop of the flattening coefficient value for the acoustic emission signal $K(AE_{rms})$ in the removed material function (Fig. 4c). Shaping of the discussed feature's value in the positive values range ($K > 0$) means that the signal values were highly concentrated but that over time the distribution was driving at the normal distribution (for which $K = 0$).In its general form, this coefficient is consistent with the grinding wheel blunting tendency – it is monotonously decreasing in the grinding time function and achieves its lowest value at the end of the analyzed period.

What was observed in the conducted tests was consistent increase of the kurtosis value $K_\beta(AE_{rms})$ and skewness drop (slant) $Sk_\beta(AE_{rms})$ of the signal for beta distribution in the removed material value – Fig. 4d. What can be determined during analysis of both values of the beta distribution parameters is the maximum after achieving of which the process may take place in unfavorable conditions due to the grinding wheel wear and decrease in the quality of the surface obtained after machining.

3.3. CORRELATION ANALYSIS

The hereby subchapter presents results of analyses of the relations occurring between selected parameters that describe samples' surface features and the statistical parameters of the registered acoustic emission signal – Fig. 5 – Fig. 7.

Due to its properties, and especially it's the sources of its origin, the AE signal is a parameter of extremely selective usefulness in the field of anticipating the resultant geometry of surface that undergoes the grinding process. In these conditions the statistical parameters that describe the AE signal RMS value AE_{rms} showed relatively high correlation with changes of the arithmetical average of the samples' surface roughness profile ordinates $Ra_{(w)}$ – Fig. 5a, 5b.

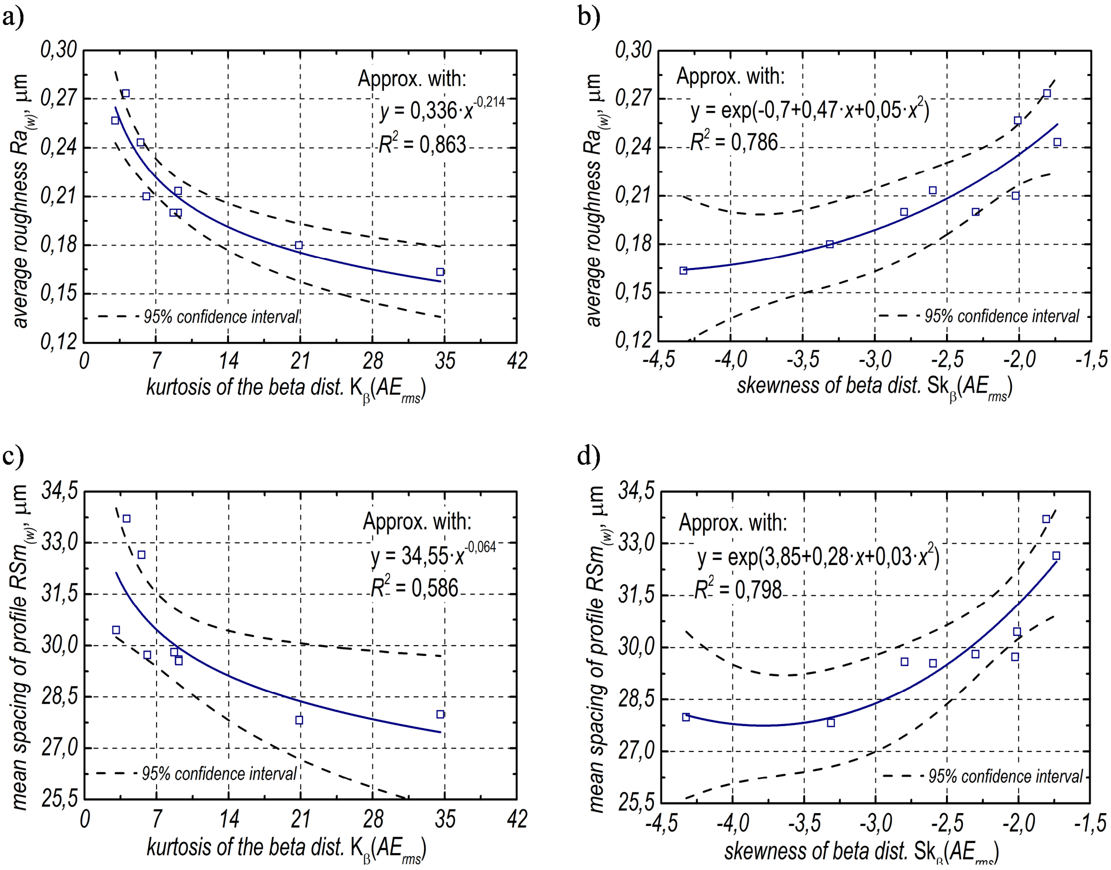

Fig. 5. Correlating amplitude and distance parameters of surface roughness in the kurtosis and skewness function of beta distribution of RMS AE value: a-b) arithmetical average deviation of the roughness profile, c-d) mean width of the roughness profile elements

The test results revealed diversified shaping of the AE_{rms} value in relation to the obtained object roughness. High values of the arithmetical average of the profile ordinates were obtained when relatively lower AE_{rms} kurtosis values were registered during the tests. An opposite situation occurred when high AE signal RMS values were registered. This means that in order to guarantee low object roughness in grinding machining the process would have to be optimized as far as registration of relatively high $K_\beta(AE_{rms})$ values are concerned. However, as previously proved, increases in the values of this parameter are indicative of the grinding wheel wear.

Taking into consideration the AE connection with the average spacing of local slopes $RSm_{(w)}$, the signal parameters are no longer such a good explanatory factor. The nature of points layout is clear enough to be able to conclude that the phenomena of shaping spacing's between the profile elements and the registered acoustic emission signal value occurred simultaneously. The correlation coefficient value (Fig. 5c, 5d) indicates better adjustment of the model with the beta distribution slant coefficient.

Similar results were obtained for the material ratio value and mean square profile slope (Fig. 6). Changes in values of both these parameters resulted from changes in the machining conditions (the tool's wear).

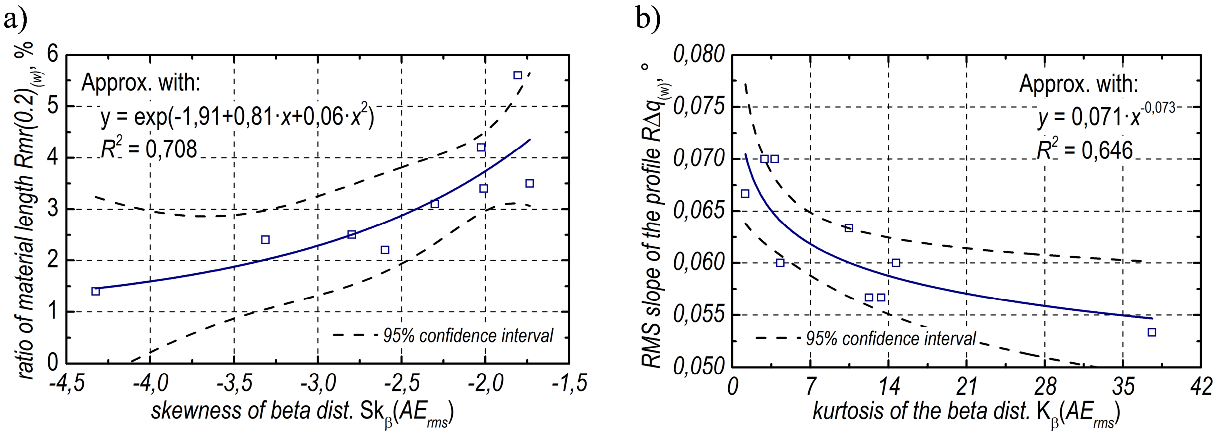

Fig. 6. Correlating hybrid parameters of roughness profile in the beta distribution parameters of RMS AE value: a) material ratio of roughness profile in function of skewness value, b) root mean square slope of the roughness profile in function of kurtosis value

On the analyzed *c* level from the highest profile apex, the total profile slopes width decreased visibly in the removed material value. This phenomenon is best correlated with the skewness of beta distribution of the acoustic emission RMS value through the exponential function (Fig. 6a).

The drop of the average roughness profile rake ($R\Delta q$) can be described in greatest detail using the power function with the use of kurtosis value of the beta distribution of the RMS AE signal value (Fig. 6b). The given model is not adequate for the experimental data but the nature of points layout is clear enough to facilitate correlation of both comparable values.

Results of correlative analyses between the acoustic emission and surface layer residual stresses are presented in charts – Fig. 7. The determined equations do not show the statistical significance (low correlation values), but the created trend lines clearly indicate that the beta distribution coefficient changes may be connected with the stress changes.

By applying the linear or root model, it can be proved that an increase of the K_β parameter or absolute value of Sk_β is connected with escalation of stresses gathering up in the workpiece surface layer. The above described analogy can be used to prevent welling up of high stresses (especially unfavorable - negative: $+\sigma_{max}$) in the workpiece surface layer. For this purpose the grinding process would have to be conducted only when relatively low flattening coefficient $K_\beta(AE_{rms})$ values and the lowest possible signal distribution slant are received from the machining zone.

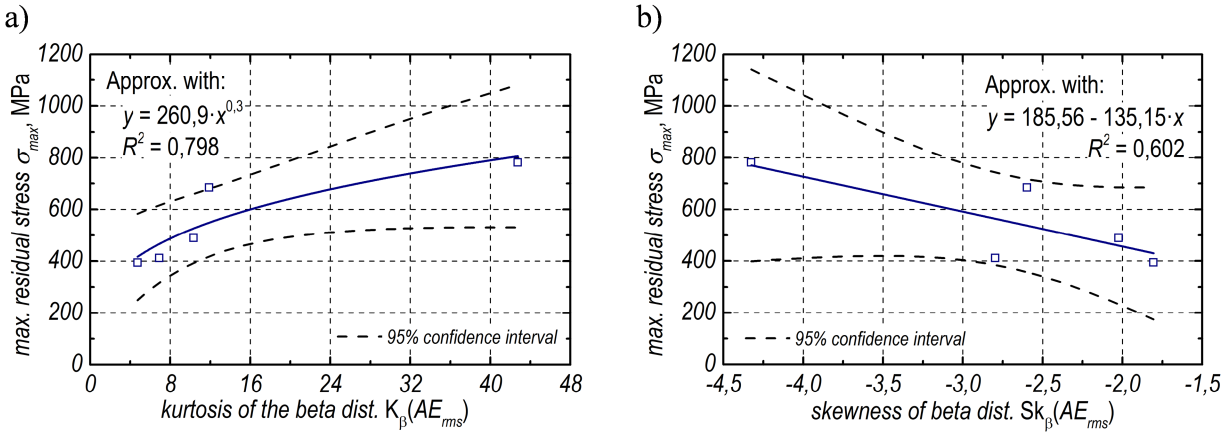

Fig. 7. Correlating maximal value of surface layer residual stress in the beta distribution parameters of RMS AE value for: a) kurtosis value, b) skewness value

It can be concluded on basis of the analysis results that in order to obtain a surface with low roughness and low stresses, the grinding process should be performed using a partially worn grinding wheel, in which the registered $K_\beta(AE_{rms})$ value is smaller than10, while $SK_\beta(AE_{rms})$ is no less than -2,5.

4. CONCLUSION

The presented research results and their analyses prove that the main source of acoustic emission signal in the grinding process is the grinding zone which, as the source of greatest plastic deformations, is the perfect research field, while the AE impulses make it possible to reflect the character of the machining conditions changes.

Monitoring the acoustic emission signals, that come from the grinding zone, allows for obtaining important information on the changes occurring over time that have significant influence on the size and nature of the influence the grinding wheel exerts on the workpiece and therefore on the geometrical changes, as well as the type and size of the stresses accumulated in the grinded material.

Application of proper AE signal analysis methods, e.g. through fuzzy logic, should allow for using the obtained dependencies in the system of grinding process diagnostics, therefore for the possibility to anticipate the microgeomterical structure and the stress value, thus minimizing the risk of obtaining undesired machining results in the form of materials of improper exploitative properties.

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