MATHEMATICAL MODELING OF PROCESSES AND SYSTEMS

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EXPERIMENTAL ACOUSTIC EMISSION SIGNALS AT COMPOSITE MATERIAL MACHINING

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***Abstract*—*The results of acoustic emission signals experimental researches at composite material machining are reviewed. It is shown, that the registered acoustic emission signal is a continuous signal with the hardly bluffly form. The statistical acoustic emission amplitude parameters at increase of composite material machining speed are determined. It is shown, that the ascending of machining speed results in ascending all acoustic emission amplitude parameters. However greatest ascending there is a dispersion of registered acoustic emission signal amplitude average level. The results of acoustic emission analytical investigations at composite material machining for a prevailing mechanical destruction its surface layer are reviewed. It is shown, that the simulation results have a good coordination with the results of experimental researches.*

Index Terms—Acoustic emission; composite material; signal; amplitude; machining; control; statistical characteristics.

I. INTRODUCTION

Composite materials (CM) have a broad application in products of aircraft, space, automotive, energy and other kinds of production. CM application in such products is stipulated by their high physical, mechanical and operational characteristics, corrosive media and temperature impact resistance. By manufacturing of CM products, practically all kinds of their macro- and micro machining have been used - turning, drilling, milling, grinding. To obtain the designed product quality, investigations are carried out, including development of control, diagnostics and engineering procedure of CM mechanical treatment monitoring methods. One of methods used for materials machining with crystal structure and CM is the acoustic emission (AE) method. The principal direction for AE use is optimization of material machining technological parameters, control and monitoring of cutting tools, as well as obtaining of the designed quality of machined surface. For technological processes optimization and mining the control methods of their parameters at CM machining is interest the matching AE experimental and analytical investigations.

II. STATEMENT OF THE TASK

The purpose of this article is the experimental and analytical investigations of AE amplitude parameters at alteration of CM machining speed.

To achieve these aims next tasks were set: to conduct experimental researches of AE amplitude parameters at ascending of CM machining speed; to conduct statistical processing of experimental AE signals with data retrieval on statistical AE amplitude parameters; to determine influencing of CM machining speed on experimental AE signals; to conduct simulation of AE signals amplitudes change depending on CM machining speed; to determine influencing of CM machining speed on AE model signals parameters.

III. REVIEW OF PUBLICATIONS

The acoustic emission investigations for machining materials with the crystal structure are based on assumptions of AE number sources existence. Such sources may be [1] – [4]: plastic deformation and destruction of the machining material; chips friction on the front facet; tool friction on the treated surface; chips destruction; impingement of chips with the treated surface; phase transformations; destruction of the processing tool, etc. At the same time, experimental research demonstrates that the process of machining materials is attended by emission two types of AE signals – continuous and pulse signals in the form of lets its amplitude. Such signals are observed by all kinds of machining materials at micro- and macro levels – turning, drilling, milling, grinding [5] – [8]. Considering for difference in energy of ongoing processes (acoustic emission energy), the first type of AE signals is related to the processes of treated material surface layer deforming and destruction during operation of cutting tool in a normal or wearing condition [4]. The second type of AE signals is mostly related to the cutting tool destruction.

Based on this, during development of control and engineering process monitoring methods for machining material (optimization of machining material parameters, evaluation of cutting tool condition and treated material surface quality), one carries out analysis of continuous AE signal parameters. In this process, the influence of different factors on the analyzed parameters of the registered AE signals is investigated [2]. Such factors are: machining material speed, feed speed; cutting tool wear and others. The following AE parameters are analyzed: mean-square amplitude value, area under signals or its accumulated value, energy count, signal count by introduction of the limiting threshold, as well as of AE signals spectra on time intervals analysis and other.

As demonstrate investigations, by different types of CM machining, registered AE signals are also continuous signals [9] – [12]. In the process of search interrelation such signal parameters' with the CM machining technological processes parameters, the above considered approaches are used.

Results of conducted investigations demonstrate that the registered AE signals possess a complicated character changing in time during machining materials. Still, the obtained empiric AE signal parameters regularities change at change of the influencing factors are not stable, and certain investigation data are contradictory. Most of the published results relate to experimental investigations. At the same time, theoretical researches related to formation and simulation of acoustic emission during machining materials are quite little in number.

In the articles [13], [14], a model of AE resulting signal is considered, which is formed during machining materials. The model is related to the treated materials with the crystal structure. In the basis of construction model are laid existing representations about sequence of material surface layers deformation and destruction processes during its machining. The mentioned development process is attended with formation of sequence AE pulse signal from plastic deformation and material destruction. Compliant to the developed model, the resulting AE signal is represented as

$$U_p(t) = \sum_j U_d(t - t_j) + \sum_i U_T(t - t_i), \qquad (1)$$

where t_j, t_i are the moments of AE signal appearance from material surface layer plastic deformation U_d and destruction U_T.

The simulation of AE resultant signals, which is conducted in articles [13], [14], with allowance the random component in time of materials surface layer deforming and destruction processes appear and development has shown, that the AE reshaped signals are continuous signals with the hardly bluffly form. The similar AE signals are recorded in the process of experimental researches [5], [14], [15]. The simulation of AE resultant signals as has shown, that the ascending of materials machining speed result to increasing of AE resultant signal amplitude average level, its standard deviation and dispersion.

The principles of AE model construction that considered in article [13] may be used to AE model construction for the case of CM machining. Thus the experimental researches of AE signals will allow not only to update the AE model, but also to determine the main approaches to optimization technological processes and selection parameters for mining methods of their monitoring and control of CM machining parameters

IV. RESULTS OF EXPERIMENTAL RESEARCHES

The experimental researches of AE signals conducted at CM cutting on the basis of silumin. CM machining conducted on a thread-cutting lathe with usage of diamond-hard-alloy lamina and lamina CD10 with by insert from PCD (polycrystallic simulated diamond, which one has a mean grit size). The scheme of realization experimental researches is shown in Fig. 1. Diameter of bar has made 71.8 mms, and its long made 165 mms. At fulfillment of researches the following CM machining parameters were used. The cutting depth h made h = 0.1 mms. The feed speed z was equal $z \approx$ 0,1 mm/return. A cutting speed V made: 100 m/min; 200 m/min; 300 m/min; 400 m/min; 500 m/min.

Acoustic emission signal registration was carried out with application of AE sensor placed at the cutter holder (Fig. 1). The signal from the sensor output was amplified and after analog data digitizer entered computer for its processing and analysis. AE signal processing was carried out with the use of software. Acoustic emission signal processing results were represented as table and graphic data. Conversion frequency of the analog data digitizer constituted 170 KHz. For every registered AE signal was performed processing of 10^6 measurement results.

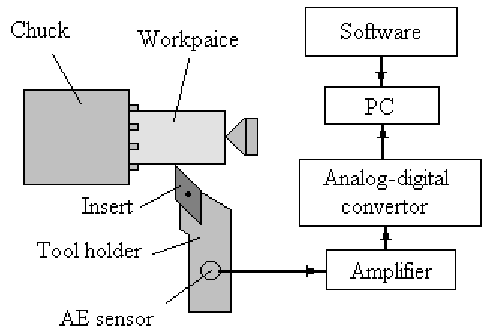

Fig. 1. Installation for experimental AE researches at silumin-based CM machining

By results of experimental researches the statistical data processing with definition of AE registered signals statistical amplitude parameters (amplitude average level, its standard deviation and dispersion) was conducted. Further was analyzed their changes at ascending of CM machining speed. The results of investigations represented as diagrams of AE signal amplitude alteration in time are provided in Fig. 2.

The investigation results (Fig. 2) demonstrate that by CM machining the registered AE signals are continuous signals with sharply cut shape. CM machining speed raise (with permanent cutting depth and feed speed) results in the increase of AE signal amplitude average level and its spread value.

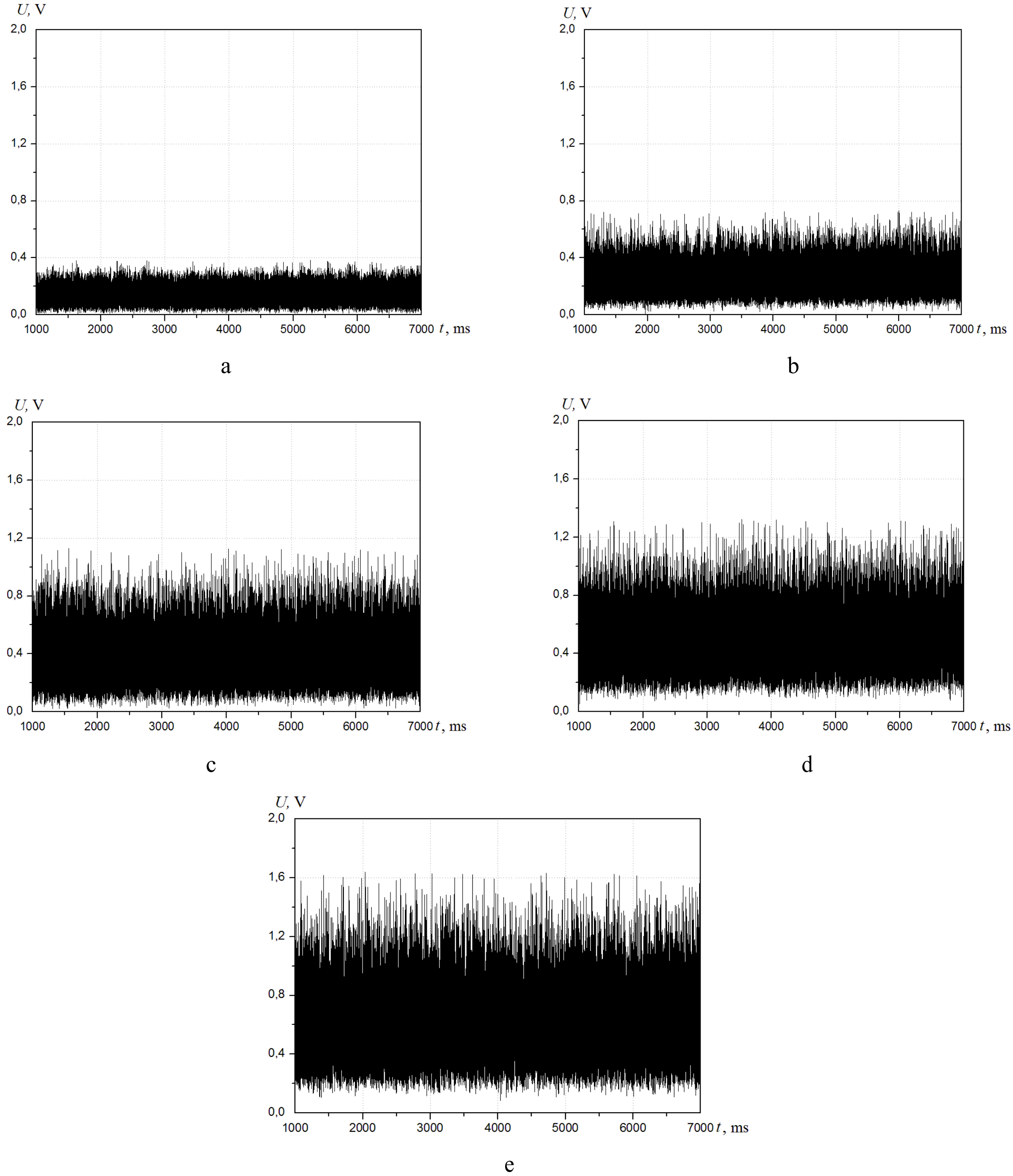

Fig. 2. Diagrams of experimental AE resulting signal amplitude alteration in time during silumin-based CM machining. Speed of CM machining: (a) - 100 m/min; (b) - 200 m/min; (c) - 300 m/min; (d) - 400 m/min; (e) - 500 m/min

Results of registered AE signal amplitude parameters statistic processing are represented in Table I. The following designations of registered AE signal amplitude parameters are used in Table I: the amplitude average level ($\bar{U}$); the amplitude average level standard deviation ($s_{\bar{U}}$); the amplitude average level dispersion ($s_{\bar{U}}^2$).

The obtained data (Table I) demonstrate, that at increase of CM machining speed from 100 m/min up to 200 m/min, i.e. in 2 times, amplitude average level ($\bar{\bar{\tilde{U}}}$) of AE signal, its standard deviation ($s_{\tilde{U}}$) and dispersion ($s^2_{\tilde{U}}$) increase, accordingly: in 1.733 times, in 1.912 times and in 3.664 times. If the machining speed is increased in 3 times (up to 300 m/min), the AE parameters $\bar{\bar{\tilde{U}}}$, $s_{\tilde{U}}$ and $s^2_{\tilde{U}}$ increase, accordingly: in 2.490 times, in 2.796 times and in 7.836 times. At ascending machining speed in 4 times (up to 400 mm/min) the AE amplitude statistical parameters $\bar{\bar{\tilde{U}}}$, $s_{\tilde{U}}$ and $s^2_{\tilde{U}}$ increase, accordingly: in 3.183 times, in 3.610 times and in 13.040 times. If the machining speed is increased in 5 times (up to 500 m/min), the parameters $\bar{\bar{\tilde{U}}}$, $s_{\tilde{U}}$ and $s^2_{\tilde{U}}$ increase, accordingly: in 3.965 times, in 4.740 times and in 22.500 times.

TABLE I

AMPLITUDE PARAMETERS OF EXPERIMENTAL AE SIGNALS

Machining speed, m/min	$\bar{U}$, V	$s_{\bar{U}}$, V	$s^2_{\bar{U}}$, V^2
100	0.1544	0.04341	0.00188
200	0.26753	0.08299	0.00689
300	0.38446	0.12137	0.01473
400	0.49147	0.15658	0.02452
500	0.61227	0.19694	0.03879

The outcomes experimental researches demonstrate, that increase of CM machining speed results in ascending all registered AE signal statistical amplitude parameters. However greatest ascending is watched in resultant AE signal amplitude average level dispersion.

V. RESULTS OF THEORETICAL RESEARCHES

The simulation of AE signals we shall conduct for a case of CM machining at prevailing mechanical destruction its surface layer (Fig. 3). Let's consider, that the CM machining implements with given and constant technological parameters. The data parameters are (Fig. 3): CM sample rotation speed, which determines of machining speed or cutting speed (α); cutting depth (h); feed speed of stride (ω). The composite materials has the given physical-mechanical characteristics.

According to existing submissions during machining there is a sequential CM surface layer elementary area (S_T) deforming and destruction. The elementary area S_T consists from N_0 CM destruction elements. We assume that deformation of each surface element takes place in the elastic region until destruction. Thus the area of each following destruction surface element is a constant value.

We assume that destruction of each surface element is attended with AE single pulse generation. We shall not take into account friction and wear of the cutting tool, as well as of possible sources of acoustic emission. Sequential destruction of CM surface elements in time would result in the sequence of AE pulse signal generation in time. Accounting for the assumed conditions, in the process of sequential destruction of CM surface elements the resulting AE signal may be represented as the amount of pulse signals sequentially generated in time

$$U_p(t) = \sum_j U_j(t - t_j), \qquad (2)$$

where t_j are time moments of AE impulse signal appearance U_j, which appear during sequential destruction of j CM surface area.

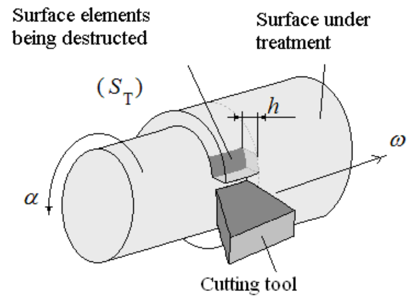

Fig. 3. Composite material specimen machining: α is the cutting speed; h is the cutting depth; ω is the feed speed

At the prevailing mechanism of CM mechanical destruction area, agrees [16], the AE pulse signal is reshaped, which is described by an expression of the following type

$$U_j(t) = u_0 t \alpha \upsilon_0 e^{r\alpha t} e^{-\frac{\upsilon_0}{r\alpha}\left(e^{r\alpha t}-1\right)}, \qquad (3)$$

where $u_0 = N_0 \psi \delta_S$ is the maximally possible elastic displacement, which extends in the material by momentary destruction of the given CM surface; N_0 is the number of CM single elements in the given destruction surface; ψ is the constant of proportionality between mechanical tension and the amplitude of single excitation impulse, which is generated by destruction of a single element (is a constant value); δ_S is the value proportional to the length of excitation impulse by destruction of a single element; α is the loading speed; υ_0, r are the constant values determined by CM physical and mechanical characteristics.

For an approaching to actual process, we shall consider that the machining descends with existence random component in time of CM surface layer elementary area destruction.

Its availability can be conditioned by existence of CM properties dispersion, instability of sample rotation speed, instability of feed speed, instability the sizes of destruction area and other factors. These factors, unconditionally, will influence on the elementary area duration destruction process and duration of reshaped AE signals pulse. Then the time t_j appearance) of each subsequent AE signal in expression (2) may be presented as

$$t_j = j\Delta t_j \pm \delta, \qquad (4)$$

where Δt_j is time interval between the beginning of the next generation AE pulse signal in regard to the previous one; $j = 0, \ldots, n$; δ is random component in time moment of appearance every next AE pulse signal.

The simulation will be carried out, in compliance with (2), considering for (3) and (4), as dependence of AE resulting signals amplitude in time in relative units. While simulation, we bring parameters, which are included in expression (3), to dimensionless quantities, and time will be represented in normalized units. Signal amplitude will be normalized for value u_0. For calculation the value of parameters υ_0 and r we assume equal to: $\tilde{\upsilon}_0$ = 100000; $\tilde{r}$ = 10000. Value α we assume equal to: $\tilde{\alpha}$ = 10; $\tilde{\alpha}$ = 20; $\tilde{\alpha}$ =30; $\tilde{\alpha}$ =40; $\tilde{\alpha}$ =50. Time interval Δt_j and the range of random component δ variation, which are included in expression (4), we shall set on the basis of duration AE signals generated pulse for the given CM loading speed $\tilde{\alpha}$.

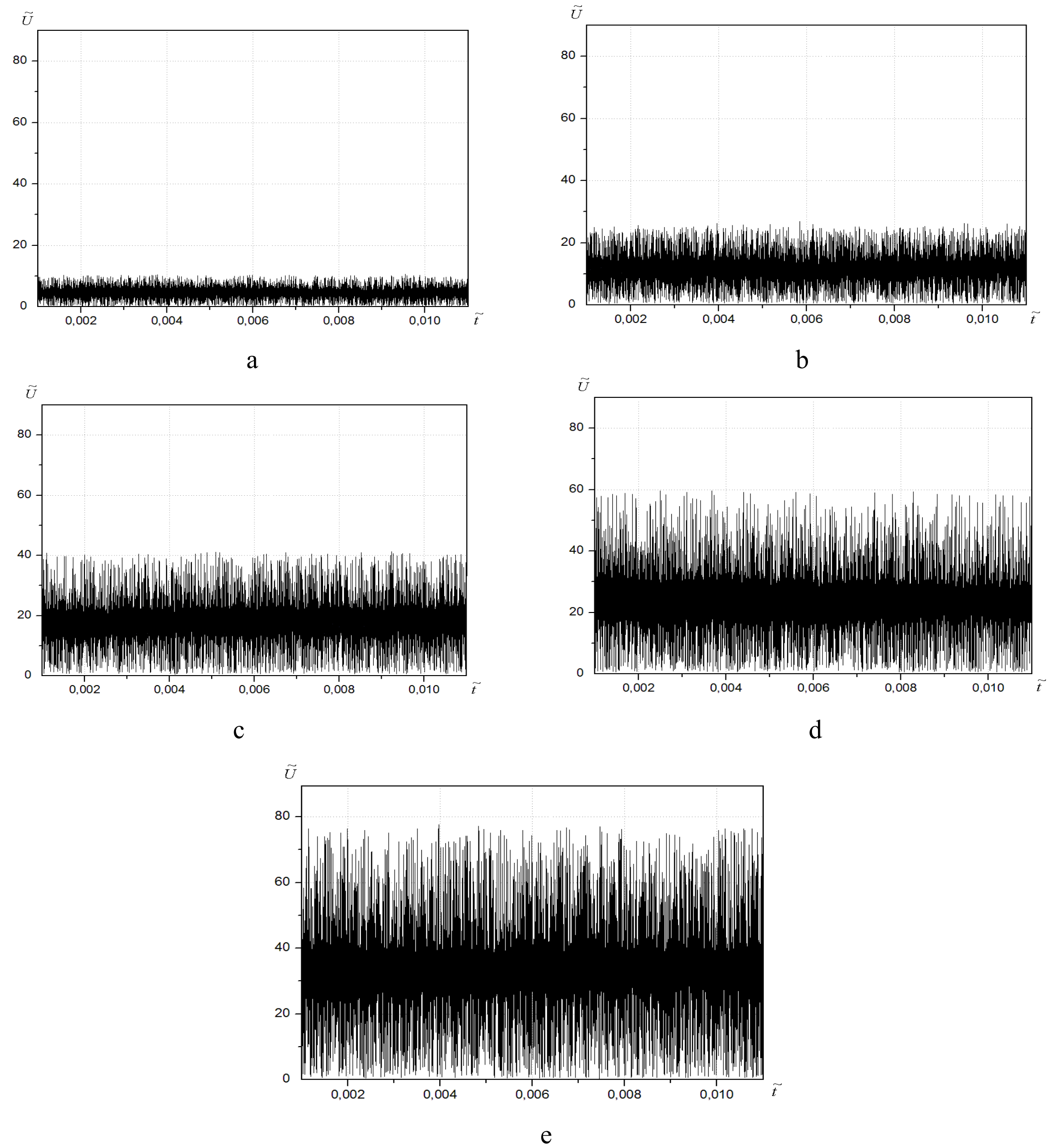

Fig. 4. Diagrams of model AE resulting signal amplitude alteration in time during CM machining. Speed $\tilde{\alpha}$: (a) - $\tilde{\alpha}$ = 10; (b) - $\tilde{\alpha}$ = 20; (c) - $\tilde{\alpha}$ = 30; (d) - $\tilde{\alpha}$ = 40; (e) - $\tilde{\alpha}$ = 50

For initial value $\tilde{\alpha}$ = 10, we'll assume value Δt_j equal to: $\tilde{\Delta} t_j$ = 0,000011. Value $\tilde{\delta}$ will be varied in the range of numbers from 0 to 0,000011 in a random way. As calculations demonstrate, according to (3), by constant values of $\tilde{\upsilon}_0$, $\tilde{r}$ and raising $\tilde{\alpha}$, the decrease of AE impulse signal duration takes place. For that reason, while simulating AE resulting signals for other $\tilde{\alpha}$ numbers, values $\tilde{\Delta} t_j$ and $\tilde{\delta}$ will be decreased pro rata to the decrease of duration AE signals generated pulse.

The outcomes of simulation of AE resultant signals amplitude change in time by the way of schedules $\tilde{U}_P(t) = U_P(t)/u_o$ introduced in normalized units are shown in a Fig. 4. By plotting of Fig. 4, there were calculated 5000 resulting signals' amplitudes for each value of $\tilde{\alpha}$. The conducted investigations demonstrate (Fig. 4) that for the accepted conditions of CM machining with prevailing mechanical destruction its surface layer, AE resulting signals are continuous signals. The signals have complicated and sharply cut form. As such signals' characteristics may use the amplitude average level, its standard deviation and dispersion. Figure 4 demonstrates that by increase of CM machining speed, while other impact factors being constant increase of the resulting AE signals amplitude average level and its spread value takes place. Table II represents the results of AE resulting signals amplitude parameters statistical processing: amplitude average level ($\tilde{\bar{U}}$); amplitude average level standard deviation ($s_{\tilde{\bar{U}}}$); amplitude average level dispersion ($s^2_{\tilde{\bar{U}}}$).

TABLE II

AMPLITUDE PARAMETERS OF MODEL AE SIGNALS

Value of $\tilde{\alpha}$	$\tilde{\bar{U}}$	$s_{\tilde{\bar{U}}}$	$s^2_{\tilde{\bar{U}}}$
10	4.67904	2.26921	5.14932
20	11.63615	5.66525	32.0951
30	18.03798	8.53515	72.84886
40	25.10965	11.89548	141.50234
50	32.67028	16.63238	276.63614

Calculation results demonstrate that by increase of $\tilde{\alpha}$ from $\tilde{\alpha} = 10$ to $\tilde{\alpha} = 20$, i.e. 2 times, the amplitude average level ($\tilde{\bar{U}}$), its standard deviation ($s_{\tilde{\bar{U}}}$) and dispersion ($s^2_{\tilde{\bar{U}}}$) are increases, respectively: by 2.487 times, by 2.497 times and by 6.233 times. If $\tilde{\alpha}$ is increase at 3 times (to up $\tilde{\alpha} = 30$), then $\tilde{\bar{U}}$, $s_{\tilde{\bar{U}}}$ and $s^2_{\tilde{\bar{U}}}$ are increases, respectively: by 3.855 times, by 3.761 times and by 14.147 times. At ascending $\tilde{\alpha}$ in 4 times (up to $\tilde{\alpha}$ = 40) the values of parameters $\tilde{\bar{U}}$, $s_{\tilde{\bar{U}}}$ and $s^2_{\tilde{\bar{U}}}$ increase, accordingly, in 5.421 times, in 5.242 times and in 27.534 times. At ascending $\tilde{\alpha}$ in 5 times (up to $\tilde{\alpha}$ = 50) the values of parameters $\tilde{\bar{U}}$, $s_{\tilde{\bar{U}}}$ and $s^2_{\tilde{\bar{U}}}$ increase, accordingly, in 7.112 times, in 7.330 times and in 53.721 times.

The obtained simulation results demonstrate that CM machining speed increase results in the increase of all AE resulting signal amplitude parameters. Still, the highest increase is observed at the AE resulting signal amplitude average level dispersion.

VI. CONCLUSION

The outcomes experimental researches of AE signals at silumin-based CM machining are reviewed. It is shown, that the AE registered signals have composite nature of change and hardly bluffly form. Increase of CM machining speed results in ascending of AE signal amplitude average level and value of its spread. The calculations of experimental AE signals statistical amplitude parameters are conducted. It is shown, that the ascending of machining speed is accompanied by ascending of all AE statistical amplitude parameters. However greatest ascending has AE registered signal amplitude average level dispersions.

The simulation of AE signals at CM machining for the prevailing mechanical destruction its surface layer is conducted. It is shown, that the AE signals have a composite nature of change. The AE model signals statistical amplitude parameters are determined. It is shown, that ascending of CM machining speed should result to increase of reshaped AE signals amplitude parameters (amplitude average level, its standard deviation and dispersion). Thus the ascending of amplitude average level dispersion should advance ascending of amplitude average level and its standard deviation.

The obtained outcomes demonstrate the good coordination experimental and analytical investigations. The obtained results can be used at mining methods of CM machining technological processes control. In further investigations, makes an interest the analysis of experimental AE signal amplitude parameters at change of CM machining cutting depth.

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С. Ф. Філоненко, Т. В. Німченко, О. В. Заріцький. Експериментальні сигнали акустичної емісії під час механічної обробки композиційного матеріалу

Розглянуто результати експериментальних досліджень сигналів акустичної емісії під час механічної обробки композиційного матеріалу. Показано, що реєстрований сигнал акустичної емісії є неперервним сигналом із сильно порізаною формою. Визначені статистичні амплітудні параметри акустичної емісії у разі зростання швидкості механічної обробки композиційного матеріалу. Показано, що зростання швидкості механічної обробки приводить до зростання всіх амплітудних параметрів акустичної емісії. Однак найбільше зростання має дисперсія середнього рівня амплітуди реєстрованого сигналу акустичної емісії. Розглянуто результати теоретичних досліджень акусти-

чної емісії під час механічної обробки композиційного матеріалу для переважного механічного руйнування його поверхневого прошарку. Показано, що результати моделювання мають добре узгодження з результатами експериментальних досліджень.
Ключові слова: акустична емісія; композиційний матеріал; результуючий сигнал; модель; амплітуда; механічна обробка; статистичні характеристики.

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С. Ф. Филоненко, Т. В. Нимченко, О. В. Зарицкий. Экспериментальные сигналы акустической эмиссии при механической обработке композиционного материала

Рассмотрены результаты экспериментальных исследований сигналов акустической эмиссии при механической обработке композиционного материала. Показано, что регистрируемый сигнал акустической эмиссии является непрерывным сигналом с сильно изрезанной формой. Определены статистические амплитудные параметры акустической эмиссии при увеличении скорости механической обработки композиционного материала. Показано, что возрастание скорости механической обработки приводит к возрастанию всех амплитудных параметров акустической эмиссии. Однако наибольшее возрастание имеет дисперсия среднего уровня амплитуды регистрируемого сигнала акустической эмиссии. Рассмотрены результаты теоретических исследований акустической эмиссии при механической обработке композиционного материала для преобладающего механического разрушения его поверхностного слоя. Показано, что результаты моделирования имеют хорошее согласование с результатами экспериментальных исследований.
Ключевые слова: акустическая эмиссия; композиционный материал; результирующий сигнал; модель; амплитуда; механическая обработка; статистические характеристики.

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