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A STUDY TO DETERMINE THE ONSET OF CATASTROPHIC WEAR OF A PROCESSING TOOL BY STATISTICAL PARAMETERS OF ACOUSTIC EMISSION

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Проведено експериментальні дослідження впливу зносу обробного інструменту на взаємну зміну статистичних амплітудних параметрів сигналів акустичної емісії. Сигнали акустичної емісії реєструвалися при точінні силуміну. Дослідження були спрямовані на пошук параметрів, які дозволяють визначати виникнення критичного зносу обробного інструменту. Показано, що реєстровані сигналі є неперервними сигналами. Проведена обробка статистичних амплітудних параметрів сигналів акустичної емісії при нормальному і катастрофічному зносі обробного інструменту. Визначено, що розвиток нормального і катастрофічного зносу інструменту приводить до зменшення значень статистичних амплітудних параметрів реєстрованих сигналів акустичної емісії. Однак особливостей в їх зміні для визначення типу зносу, що розвивається, не спостерігається. У той же час, на різних часових інтервалах фіксується випереджальне збільшення або зменшення одного з статистичних амплітудних параметрів сигналів акустичної емісії.

Проведена обробка коефіцієнта, який характеризує взаємну зміну статистичних амплітудних параметрів реєстрованих сигналів. Визначено, що відсутність зносу інструменту характеризується стабільними значеннями розрахункового коефіцієнту в часі. Виникнення і розвиток катастрофічного зносу приводить до викиду значення розрахункового коефіцієнту з наступним його прискореним зменшенням до руйнування інструменту. Виникнення і розвиток нормального зносу приводить до зростання значення розрахункового коефіцієнту з наступним переходом до пилкоподібного його змінення і поступового зменшення його величини. Отримані закономірності можуть бути використані при розробці методів контролю і моніторингу стану обробного інструменту при механічній обробці матеріалів, включаючи і моніторинг стану обробного інструменту в роботизованих виробництвах

Ключові слова: акустична емісія, композиційний матеріал, статистичні амплітудні параметри, механічна обробка матеріалів, зношування обробного інструменту

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1. Introduction

The method of acoustic emission (AE) is widespread in researching technological procedures of mechanical processing. This is due to the high sensitivity of the method to the processes of deformation and fracture of materials, as well as its low inertia to them. At the same time, significant amounts of information that reflect the dynamics of involved processes entail the problem of its interpretation. The problem is complicated by the influence of various factors on the parameters of recorded AE signals. The presence of these problems results in general patterns of change in the statistical parameters of AE signals, which are used to develop methods for controlling and monitoring the state of the cutting tool. However, the general tendencies in reducing the statistical parameters of AEs make it possible to determine the development of tool wear without identifying its type (normal, catastrophic), which reduces the reliability of the methods for controlling and monitoring the state of the cutting tool. Meanwhile, studies show that, in the presence of general tendencies in the decrease in the statistical parameters of AE, the rates of their changes differ. It is important to determine the regularities characterising the mutual change in the statistical parameters of AE during the development of various types of wear of the processing tool as it helps devise methods for monitoring its condition, and first of all, solve the problem of identifying the occurrence of critical wear of the processing tool.

2. Literature review and problem statement

One of the factors that affect AE during the machining of materials is the wear of the processing tool. Studies show that when turning various materials and with the occurrence of wear of the processing tool, AE signals are continuous. For example, when turning high-carbon steel AISI-D3 [1], structural steel C45 [2], alloy Ti-6Al-4V [3]. However, when the tool is worn, the parameters of the registered AE signal change. In [4], it is shown that when the wear of a processing tool occurs, the amplitude of the recorded AE signal decreases. In this case, a decrease in the amplitude of the carrying frequency in the low-frequency spectrum of the detected AE signal is observed. However, the statistical energy parameters of AEs have a complex pattern of change. With increasing wear of the processing tool, there is a tendency to decrease the average level of the amplitude of the AE signal and its standard deviation. In this case, the root mean square (RMS) amplitude of the AE signal increases. At the same time, a decrease in the asymmetry coefficient of the amplitude distribution of AE signals is observed, and the excess coefficient increases.

In [5], it is determined that at the initial and final stages of machining a composite, the parameters of the recorded AE signals differ. The onset of wear of the processing tool with peeling of the coating leads to a decrease in the root mean square value of the amplitude of the AE signal. In this case, a decrease in the amplitude of low-frequency components in the spectrum of the AE signal is observed. It is shown in [6] that an increase in the wear of a processing tool leads to a decrease in the amplitudes in the energy spectrum of the recorded AE signal. In [7], it is proved that with the transition from the initial to the final stage of mechanical processing of a composite, an increase in the RMS amplitude of the AE signal occurs. A similar dependence of the change in the RMS amplitude of the AE signal is preserved with an increase in the longitudinal feed rate of the cutter. According to the authors, such an increase in the RMS amplitude of the AE signal is due to the change in the conditions of contact interaction of the processed and processing materials when wear occurs. A similar result of an increase in the RMS amplitude of the AE signal is obtained in [8]. In [9], tests are performed on the statistical energy parameters of AE during the mechanical treatment of a composite. It is shown that with an increase in the machining time of the composite, the energy of the recorded AE signal increases. In this case, at the initial stage, the asymmetry coefficients and kurtosis of the energy distribution of AE signals do not change significantly. However, when some machining time is reached, their sharp (stepwise) decrease occurs, which is associated with the occurrence of a certain level of wear of the processing tool. An analysis of the b-parameter of the β-distribution of energy of AE signals has shown that its rate of change is also observed at the same level of wear of the processing tool.

In [10], it is determined that with increasing wear of the processing tool and the cutting depth, the amplitude of the AE signal increases. It is shown in [11] that when the tool wear occurs and develops, the energy spectrum of the AE signal changes, in which the low-frequency components prevail. AE energy during tool wear is studied in [12]. It is shown that with increasing wear of the processing tool, a non-linear increase in the stored energy of the AE signals occurs. In [13], it is noted that the parameters of the initial AE signal do not make it possible to determine the state of the cutting tool. However, when filtering the signal at a certain frequency before the destruction of the instrument, an increase in AE energy is observed. In this case, at the time of instrument destruction, a sharp jump in the energy of AE signals is recorded.

To increase the reliability of controlling and monitoring a tool wear, a joint data analysis, or the principal component analysis (PCA), is used [14]. The method is based on establishing a data table according to the results of measuring various parameters, including cutting forces, AE signals, and vibrations. The data are processed to obtain a set of new orthogonal variables, called the main components, i. e., features that are subsequently used to characterise and analyse the developing process. The use of the PCA method when performing a machining operation is considered in [15]. In the study of the technological process, three cutting forces, three values of acceleration and the RMS amplitude of AE signals are measured. Based on the measurement results, the data are processed to calculate a covariance matrix, eigenvectors and eigenvalues that represent a set of new data or principal components. Processing the set of new data helps classify the status of the cutting tool or the wear state of the cutting tool. The use of the principal component analysis in machining materials to assess the wear of a cutting tool has also been considered in a number of other studies – in the processing of Inconel 718 alloy [16], normalised steel [17], and Ti-6Al-4V alloy [18].

Theoretical experiments on the statistical amplitude and energy parameters of AE during tool wear with controlled and uncontrolled cutting depths are considered in [19, 20]. It has been shown that during machining of a composite, the occurrence of wear of the cutting tool does not affect the nature of the acoustic emission – the radiation is continuous with a strongly rugged shape. However, with a managed (controlled) cutting depth, an increase in the tool wear leads to an increase in all statistical parameters of AE signals. With an uncontrolled depth of machining, an increase in the tool wear leads to a decrease in all statistical parameters of AE signals. At the same time, with increasing the tool wear, a change is observed in the rate of the increase or decrease in the statistical amplitude-energy parameters of AE.

The research results obtained by various authors show the ambiguous effect of tool wear on changes in AE parameters. Regularities of changes in various statistical parameters of AE during tool wear, as a rule, are smooth in nature without features helping to determine the transition to critical tool wear. This complicates processing methods such as PCA. However, the use of PCA is aimed at determining the level of the tool wear, rather than the critical stage of its development. At the same time, theoretical studies show that with the occurrence and development of tool wear, the rates of change of the AE statistical parameters differ. Of course, of interest is to determine the influence of the type of developing wear of the cutting tool on the patterns of mutual change in the statistical parameters of acoustic radiation.

3. The aim and objectives of the study

The aim of the present study is to identify the effect of wear of the processing tool on the mutual change in the statistical amplitude parameters of AE signals. This will determine the occurrence of critical wear of a tool and its timely removal from the cutting zone before failure.

To achieve the aim, the following objectives were set and done:

– to determine the patterns of change in the statistical amplitude parameters of the experimental AE signals under no, normal and catastrophic wear of the processing tool;

– to find the regularities of change in the coefficient characterising the mutual change in the statistical amplitude parameters of AE signals under no, normal and catastrophic wear of the processing tool.

4. Methods and materials for experimental tests on AE signals during wear of a processing tool

Experimental tests were carried out during mechanical processing of silumin, using a turning operation. Silumin belongs to the group of materials based on Al-Si-Cu. The chemical composition of the processed material is given in Table 1. The test samples underwent treatment according to the T1 mode – artificial aging without preliminary hardening (heating to 210±10 °C, tempering for 12 hours). The material had the following mechanical characteristics: temporal tensile strength – 186 MPa (or 19 kgf/mm^2) and Brinell hardness – 90 HB. The length of the workpiece was 165 mm, and the diameter of the workpiece was 71.8 mm.

The mechanical processing was carried out on a two-coordinate screw-cutting lathe TPK 125 VN. CD10 plates with Sandvik Coromant serial cutting inserts made of synthetic polycrystalline diamond (PCD) were used as processing tools. The inserts had a sharpening angle of 80°, a rear angle of 5°, and a tip radius of 0.4 mm. The CD10 plates were mounted in a CoroTurn 107 holder.

Table 1

The chemical composition of the processed material

Mass fraction, % of the principal components						
Magnesium	Silicon	Manganese	Copper	Titanium	Nickel	Aluminium
0.85–1.35	11–13	0.3–0.6	1.5–3.0	0.05–0.2	0.8–1.3	Base

For registration and processing of AE signals, an AE system was used consisting of an AE sensor, a signal amplifier, an input/output (I/O) port, a personal computer, and mathematical software. The AE sensor was made of piezoceramics PZT-19. The operating frequency band of the sensor was 100–2,000 kHz. The noise level of the AE signal amplifier, brought to its input, was 3.5 μV, the gain was 84 dB, and the frequency range was 100–2,000 kHz. The ADA 1406 port was used as the I/O port. The maximum sampling frequency of the analogue signal was 300 kHz. The sensitivity of the ADC was 1.22 mV per unit of the least significant bit. The software for the AE system made it possible to record the initial AE signals and process them. The processing of the registered signals consisted in converting and storing data in formats for the possibility of statistical analysis in mathematical applications for Windows.

The diagram of the installation for the tests is shown in Fig. 1.

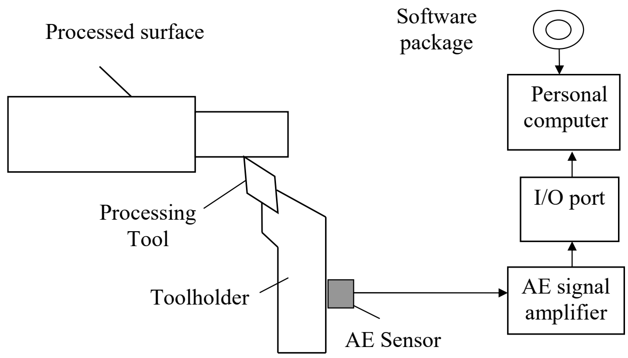

Fig. 1. The installation diagram for the experimental tests on AE signals

The experiments were carried out with the following technological parameters of machining: cutting speed – 100 m/min, cutting depth – 0.1 mm, and the speed of the longitudinal feed of the cutter – 0.1 mm/rev. Upon completing the machining operation, the linear wear of the tool was measured. During cutting, AE signals were recorded. The AE sensor was mounted in the tool holder. To ensure acoustic contact, the surface of the sensor was coated with Ramsay grease. AE signals from the sensor output were amplified, converted into digital codes, and recorded in a personal computer. The sampling frequency of the input analogue signal was equal to 170 kHz. The maximum amount of recording AE information was 4 GB.

5. Results of registering AE signals during wear of the processing tool

Fragments of typical experimental AE signals at various stages of machining for the two cutters used are shown in Fig. 2. The AE signal in the graph of Fig. 2, *a* corresponds to the initial stage of machining the material. The AE signals in Fig. 2, *b* and Fig. 2, *c* correspond to the final stage of machining. In this case, the AE signal (Fig. 2, *b*) was detected during intensive wear of the first processing tool and its destruction (point *A*, Fig. 2, *b*). The AE signal (Fig. 2, *c*) was detected during normal wear of the second processing tool without its destruction. The linear wear of the second processing tool was 0.05 mm.

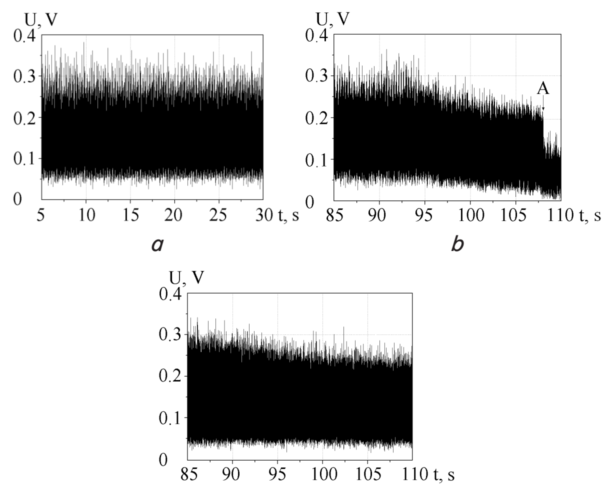

Fig. 2. The change in the amplitude of the AE signals over time during the machining of the material: *a* – the initial stage without wear of the cutter; *b* – the final stage with catastrophic wear of the processing tool; *c* – the final stage with normal wear processing tool. Point *A* in Fig. 2, *b* corresponds to the moment of the tool destruction

The results obtained show that the recorded AE signals are continuous, with a strongly rugged shape. With the occurrence and development of wear of the processing tool (normal and catastrophic), the nature of the acoustic radiation does not change. However, a decrease in the amplitude of AE signals is observed (Fig. 1, *b*, *c*). Moreover, the destruction of the instrument leads to a sharp drop in the amplitude of the AE signal.

6. Patterns of changes in the statistical amplitude parameters of AE during wear of the processing tool

The statistical amplitude parameters of the AE signals shown in Fig. 2 were determined. The results of the calculations, in the form of graphs of changes in the average amplitude (AA) of AE signals over time, are shown in Fig. 3. In the calculations, the analysis interval was 1 s.

According to the data obtained, at the initial stage of the mechanical processing of the material, a certain stability of the AA of AE signals is recorded (Fig. 3, *a*). Such stability of the AA is observed until the time of occurrence of wear of the processing tool. For the AE signal shown in Fig. 2, *b*, the stability of the AA is observed until 94 s of machining the material (Fig. 3, *b*). After 94 s, there is a decrease in the values of the AA. For the AE signal shown in Fig. 2, *c*, the stability of the AA is observed until 88 s of machining (Fig. 3, *c*). After 88 s, there is a decrease in the values of the AA. However, as calculations show, with the development of catastrophic tool wear, the rate of reduction of the AA of the AE signal is much higher than with the gradual (normal) wear of the processing tool. Similar patterns are observed in the change in the standard deviations and variances of the average amplitude rate of AE signals.

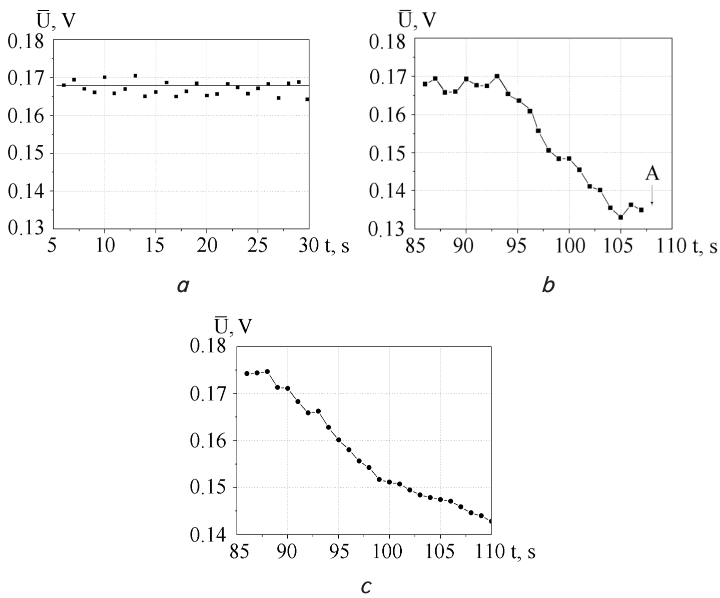

Fig. 3. The change in the average amplitude of the AE signals over time during the machining of the material: *a* — the initial stage without wear of the processing tool; *b* — the final stage with catastrophic wear of the processing tool; *c* — the final stage with normal wear of the processing tool. Point *A* in Fig. 3, *b* corresponds to the moment of the tool destruction

At the same time, as the calculations show, at different stages of machining, there is an anticipating change in one of the statistical amplitude parameters (SAPs) of AE signals.

Let us calculate the dimensionless coefficient K_U, which is the ratio of the average amplitude of the AE signal to its standard deviation at the given intervals of analysis:

$$K_U = \frac{\overline{U}}{s_{\overline{U}}}, \quad (1)$$

where $\overline{U}$ is the average amplitude of the AE signal, and $s_{\overline{U}}$ is the standard deviation of the average amplitude of the AE signal.

The dimensionless coefficient K_U characterises the ratio of the mutual change in the average amplitude of the AE signal and its standard deviation at a given interval of analysis.

The results of the calculations for the AE signals shown in Fig. 2, in the form of dependences of changes in K_U over time, are shown in Fig. 4.

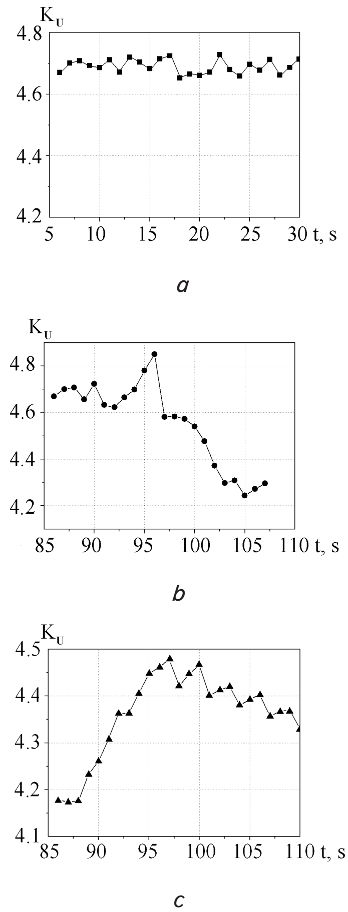

Fig. 4. The change in the coefficient K_U according to (1) in time: *a* — the initial stage without wear of the processing tool; *b* — the final stage with catastrophic wear of the processing tool; *c* — the final stage with normal wear of the processing tool

According to the data obtained, until the time of occurrence of the tool wear, certain stability is observed in the value of K_U (Fig. 4, *a*; until 94 s in Fig. 4, *b*; until 88 s in Fig. 4, *c*). After that, the nature of the change in the value of K_U is different. For the signal shown in Fig. 2, b, an outburst of the K_U value is observed (Fig. 4, *b*) with its subsequent accelerated decrease until the tool breaks. For the signal shown in Fig. 2, c, an increase of K_U is observed with its subsequent sawtooth decrease (Fig. 4, *c*).

When the analysis interval is reduced to 0.5 s, the studied regularities of changes in the AA of the AE signals and the coefficient K_U are preserved.

7. Discussion of the results of studying AE signals during wear of the processing tool

The results obtained show that during mechanical processing of the material, the occurrence and development of wear of the processing tool (normal and catastrophic) leads to a decrease in the AA of AE signals. The regularities of the AA reduction are smooth in the nature of change, which prevents determining the type of the developing wear (Fig. 3, *b*, *c*). At the same time, the coefficient characterising the ratio of the average level of the AE signal amplitude to its standard deviation at a given analysis interval is sensitive to the stages and mechanisms of the tool wear. The patterns of its change under no, normal and catastrophic wear differ.

In the absence of a tool wear, there is stability in the values of K_U (Fig. 4, *a*). When catastrophic tool wear occurs and develops, an outburst of the K_U value is observed with its subsequent accelerated decrease until the tool breaks (Fig. 4, *b*). A similar nature of the change in K_U is due to the fact that when catastrophic wear occurs (instantaneous damage to the surface layer of the tool), there happens an instantaneous decrease in the standard deviation with respect to the AA of the AE signal. A further decrease of K_U (Fig. 4, *b*) with the development of catastrophic wear is due to an anticipating decrease in the AA of the AE signal with respect to its standard deviation. With the occurrence and development of normal tool wear, the value of K_U increases (Fig. 4, *c*) with a subsequent transition to a sawtooth change and a gradual decrease of its size. A similar nature of the change of K_U is due to the fact that the occurrence and development of normal tool wear is accompanied by an anticipating decrease in the standard deviation of the AA of the AE signal relative to its average level. The transition to a sawtooth change of K_U (Fig. 4, *c*) with its gradual decrease is due to the transition to the emergence of a staged instantaneous tool wear (gradual accumulation of damage and destruction at various levels). Such process is accompanied by alternation of an anticipatory decrease in the average amplitude of the AE signal or its standard deviation.

The peculiarities of the regularities of the K_U change can be used in the development of methods for controlling and monitoring the state of the cutting tool during the machining of materials. Moreover, it should be noted that the estimated results show insignificant rates of the K_U change over time, which may affect the identification of the initial stages of the emerging type of the tool wear. First of all, this refers to the turning of flexible materials, for which, in comparison with composites, acoustic radiation is characterised by lower values of the parameters.

To solve this problem, it is necessary to study the most capacious energy parameters of AE signals.

8. Conclusion

1. The study has determined the regularities of changes in the statistical amplitude parameters of the experimental AE signals under no, normal and catastrophic wear of the processing tool. It is shown that the occurrence and development of normal and catastrophic wear leads to a gradual decrease in the statistical amplitude parameters of AE signals. In this case, no peculiarities of their change are observed to determine the type of the developing tool wear.

2. The regularities of changes are determined for the coefficient characterising the mutual change in the statistical amplitude parameters of AE signals over time under no, normal and catastrophic wear of the processing tool. It is shown that absence of the tool wear is characterised by stable values of the calculated coefficient over time. The occurrence and development of catastrophic wear leads to an outburst of the value of the calculated coefficient, followed by its accelerated decrease to the destruction of the tool. As the calculations show, in the time interval before the occurrence of critical tool wear, the average coefficient is 4.67. At the time of its outburst, its value increases stepwise by 3.72 %, followed by a sharp drop by 5.6 %. The emergence and development of normal tool wear leads to an increase in the value of the calculated coefficient with a subsequent transition to a sawtooth change and a gradual decrease of its size. Differences in the regularities of change in the calculated coefficient can be used when devising methods for controlling and monitoring the type of the developing wear of a cutting tool.

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