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Energy parameters of acoustic emission signals at friction of surfaces of composite materials

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Abstract
The results of processing of energy parameters of acoustic emission signals at friction of surfaces of composite material samples were considered. It is shown that the increase in axial load for friction units increases the median of average and total energy of registered acoustic emission signals. In addition, this increases their variance and standard deviation. It was determined that such increase of analysed parameters have nonlinear manner. It was established that increase in

variance and standard deviation for total energy is greater than for average energy of acoustic emission signals.
Keywords: ACOUSTIC, EMISSION, SIGNAL, COMPOSITE MATERIAL, LOAD, SIGNAL ENERGY, FRICTION SURFACES, SIGNAL PARAMETERS

Problem statement

Modern technical systems require large financial costs for operation and maintenance. In this regard, usage of materials which have high wear-resistance is increased. Often they are used as coatings of surface parts. Such materials include composite materials. Despite improved wear-resistance of friction units of coated composite materials, as well as for materials with a conventional structure, the problem of diagnosis is an important technical problem of monitoring and evaluating of resource of any tribosystems. The solution of this problem is based on a set of theoretical and experimental researches of friction involving various high-sensitivity methods. Among many existing methods one of the most promising is the method of acoustic emission (AE). The main advantages of AE method include high sensitivity to the processes occurring in the submicro-, micro- and macrolevels, greater penetrability, quick indication of defects and damage in real time, ability to control at one-sided access to the test object, high level of automation of diagnostic system.

Despite significant advantages of AE method, its application in research practice involves considerable difficulties. This is due to significant volumes of integrated information, contribution into which is performed at all levels of the processes developing in the surface layers of materials at their destruction. Availability of this information complicates its unambiguous interpretation, especially under the action of many different factors. In this connection, theoretical and experimental studies of AE radiation at friction and wear of surface layers of composite materials based on the influencing factors are an important area of research. This enables to determine common patterns of change in the parameters of acoustic radiation. The use of such laws of change of AE parameters in technical diagnostics of friction units are aimed at the development of methods of control, mode optimization, as well as solution of the issue of tribosystem lifetime extension.

Analysis of recent researches and publications

Theoretical and experimental studies of AE signals at surface friction of materials are considered in [1–8]. They relate to materials with different structures. Model of AE resultant signal generated at friction of surfaces for materials with traditional structure is considered in [8], and composite materials in [9]. The models are based on the laws of destruction of surface layers of materials, as well as kinetics of destruction process, the speed of which can increase in time. The difference between the models is in consideration of the specifics of destruction process. In the first case, we considered destruction of secondary structures of the I and II types. In the second case, the model is based on the concept of FBM (fibre bundle model) and kinetics of destruction [10, 11] when destruction of composite surface is considered as a process of successive destruction of its projections in the areas of contact interaction samples. Thus, under the action of transversal load rule “OR” is typically used, wherein composite material element destruction occurs either due to bending stresses or due to stretching stresses. The expression for the resultant AE signal generated at destruction of the surfaces of composite material obtained in [9], is as follows

$$U_p(t) = U_1(t-t_1) + \ldots + U_j(t-t_j) = \sum_j U_j(t-t_j), \quad (1)$$

where j – ordinal number of j-th destructible area of contact interaction; $U_j(t-t_j)$ - j-th AE pulse signal, formed on the j-th site of contact interaction (fig.1).

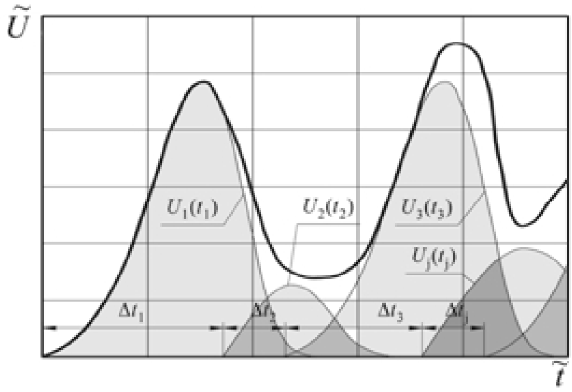


Figure 1. Formation of the resultant AE signal in time, according to (1), in arbitrary units at friction of mating surfaces

According to the model, the resultant AE signal at surface friction of composite material is the sum of elementary pulse signals generated by destruction of elementary surfaces, consisting of a predetermined number of elements. In this case elementary pulse signal according to [11], is described by the following expression

$$U(t) = U_0\, \upsilon_0 [\sigma(t) - \sigma_0(t_0)] \times e^{r[\sigma(t)-\sigma_0(t_0)] - \upsilon_0 \int_{t_0}^{t} e^{r[\sigma(t)-\sigma_0(t_0)]} dt}, \qquad (2)$$

where U_0 – is maximum possible displacement of instantaneous destruction of the elements on the platform of contact interaction; υ_0, r – are constant depending on physical and mechanical properties of composite material; $\sigma(t)$ – is equivalent stress in time which describes stretching and bending forces.

Maximum possible displacement and equivalent stress can be determined respectively as

$$U_0 = N_0\, \beta\, \delta_S \qquad \sigma(t) = \alpha\, t (1 - \alpha\, t)(1 - g\sqrt{\alpha\, t}\,)$$

N_0–original number of items on the platform of contact interaction; ß– coefficient of proportionality; δ_s– parameter (numerical value) determined by the shape of a single pulse perturbation at failure of one element (has dimension of time); α - loading rate of the material; t, t_0 – respectively, the current time and the start time of destruction of the elements; g – factor depending on the geometry of the elements.

Conducted experimental studies [12, 13] showed that at friction of surfaces of composite material a continuous AE signal with highly rugged form is formed. With increasing of rotation speed of the friction pair increase in average level of the amplitude of the resultant AE signal is observed (median in the distribution of the amplitudes of a predetermined range of analysis), as well as the value of its spread. Increasing of rotation speed of the friction pair, according to the simulation results [9], should lead to increase of the values of variance and standard deviation of average level of the amplitude of the resultant AE signal. Processing of simulation results also shows that depending on changes in average level of the amplitude of the resulting signal AE values of its variance and standard deviation with a high probability is described by nonlinear increasing function. The results are in good agreement with the results of experimental studies.

Analysed parameters, such as average amplitude of the resultant AE signal value of its variance and standard deviation, of course, can be used as reference parameters. However, their increment, as analysis of amplitude characteristics of the resulting signals shows, is not considerable. At the same time, the most far-reaching option is the energy of AE signals, which reflects all energy levels of the processes developing in surface layers of the materials. Therefore, analysis of energy parameters of AE signals which are registered at changing of operational load on the friction pair is of interest.

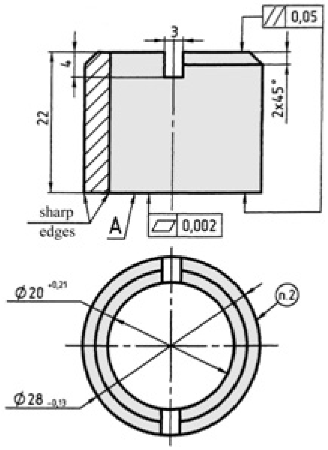
Research methods

Research of AE radiation in friction was performed on the stage of normal wear on samples of aluminium alloy D16 with carbide coating VC-6 and alloyed steel 30HGSA. The test was performed using samples of constructive interaction scheme “disk drive” on the upgraded testing machine with computer control. The samples were hubs (Fig. 2a) the contacting interaction of which was performed on the end faces. In accordance with the scheme of the test sample with carbide coating was fixed, and another sample of steel 30KhGSA rotated at a predetermined constant speed. On the end surfaces of the fixed contact interacting samples grooves were plotted (Fig. 2b). The ratio of the total area of the end surface to the end surface of the contacted area was characterized by overlap ratio. Its value varied in the range from 0.25 to 1.0.

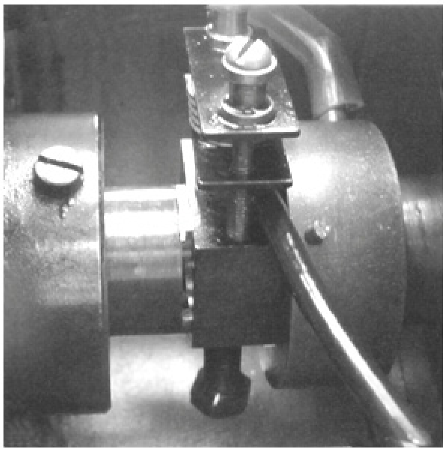
Computer control provided both predetermined rotational speed of the moving sample and necessary axial load on the stationary sample. Rotational speed of the movable specimen throughout the test remained constant at n = 600 min^{-1}, operating load P varied in the range from 300 H to 750 H in increments of 150 N, which is given by means of electric machine friction CMT-1.

In the experiments, oil of M10G2K type [14] with flow rate of 1.2 litres per hour was used as lubricating agent.

To register AE signals generated at wear of surfaces of the test specimens, the AE sensor was mounted on a fixed sample. Before installing the sensor was lubricated with surface acoustic-transparent grease. The resultant signals from the output of the AE sensor entered amplification path, and then mobile AE diagnostic system, where their processing was performed with formation and storage of necessary data sets. Average and total energy were used as the main parameters of the resultant AE processed signal. The results of processing were displayed on the screen in the form of a graph and converted into formats for mathematical applications for Windows.



(a)

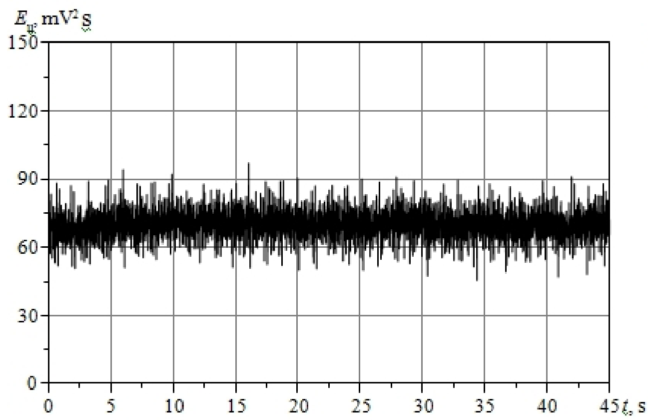


(b)

Figure 2. Detail drawing pattern (a) and general scheme of samples with coating (b) for the wear test

Experiment results

Experimental studies showed that the resultant AE signals registered by given values of axial load and constant of rotation speed of the friction pair, represent continuous signals with some middle-average the total energy and the values of their spread (Fig. 3, Fig. 4).



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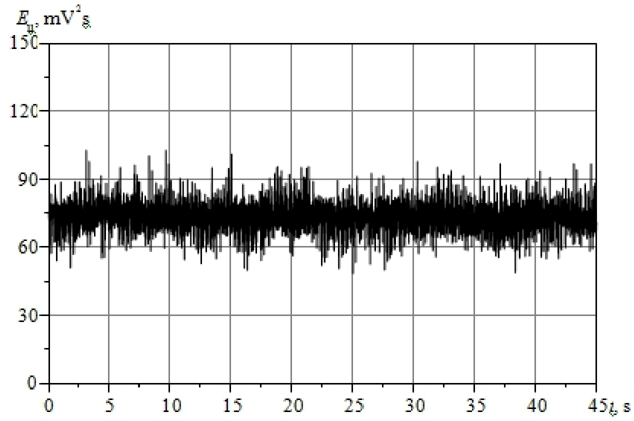

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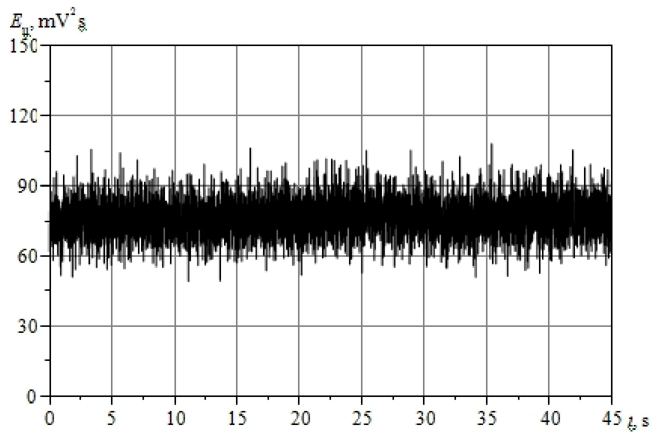
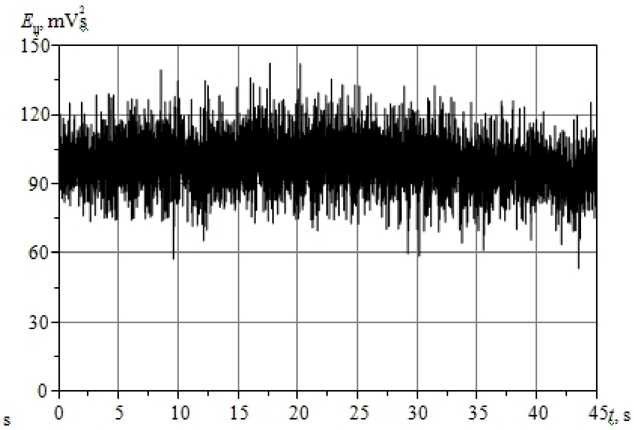


(c)



(d)

Figure 3. Graph of average energy of the resultant acoustic emission signals in time registered during wear tests of the friction pair with coating of composite material BK-6 for different values of axial loads. The value of load P: a - 300 N; b - 450 N; c - 600 N; d - 750 N. Averaging time t_a = 15 ms

For all investigated values of axial loads, resultant behaviour of AE signals is similar. AE signals have very rugged form. The resultant signals generated by AE, shown in Fig. 3 and Fig. 4, were obtained for averaging time t_a = 15 ms. Selecting of averaging time t_a is due to the need of minimizing of the loss of contribution of the components of the processes in the resultant signal AE. Experimental data [12] showed that at values of sampling interval t_a = 16 ms and more decrease above the average and median total energy resultant AE signals is observed. In the range from 5 ms to 16 ms median values of analysed parameters remain constant. Such a change in the values of the parameters analysed, is obviously due to the fact that increase in the averaging interval leads to a smoothing (filtering) process, contributing to the resultant AE signal.

In the optimum range of the averaging interval fairly slow change in dispersion and standard deviation of the median of the analysed parameters is observed. Note that statistical data processing for all test velocities in the range of analysis t_a = 15 ms showed that the probability 0.95 of distribution of average and total energy signals at predetermined intervals averaging are described by normal law distribution. The length of the sample for analysis was unchanged and the number of intervals over the length of the analysis sample was equal to 3000. Fig. 3 and Fig. 4 show that increase in axial load on the friction pair leads to increase of average energy levels of resulting AE signals and values of their variation. This is especially observed in dependence of the change of total energy of the resultant AE signals (Fig. 4).

We define values of medians $\overline{E}_{mu}$ and $\overline{E}_{ms}$ (average and total energy of the resultant signals AE) in the distributions, as well as their standard deviations and variances.

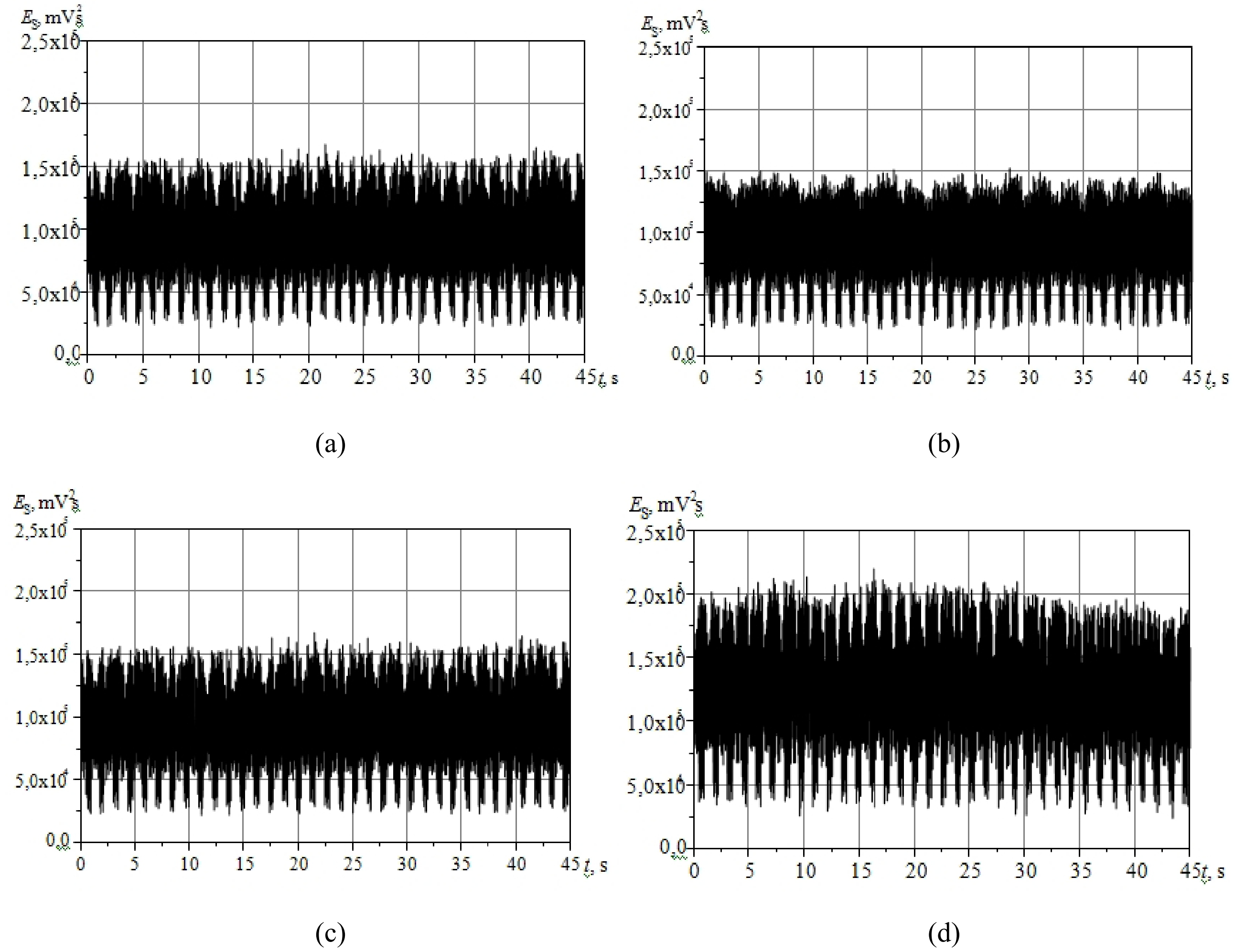


Figure 4. Graph of total energy of the resultant acoustic emission signals in time registered during wear tests of the friction pair with coating of a composite material BK-6 for different values of axial loads. The value of load P: a - 300 N; b - 450 N; c - 600 N; d - 750 N; t_a = 15 ms

Experimental data processing showed that at axial load of 300 N the median of average energy of the resultant AE signal is $\overline{E}_{mu3}$ = 69.84882 mV²s and variance and standard deviations, respectively, are: D_{Eu3}=44,32409 mV⁴s² and σ_{Eu3}=6,65763 mV²s. Increasing of axial load on the friction pair by 1.5 times, i.e. 450 H leads to increase of $\overline{E}_{mu4}$ by 1,054 times ($\overline{E}_{mu4}$ = 73,6074 mV²s). For the given axial load variance D_{Eu4} increases by 1.197 times and standard deviation σ_{Eu4} by 1.094 times. Further increase in axial load on the friction pair by 2 times, i.e. 600 H leads to increase of $\overline{E}_{mu6}$ by 1,092 times ($\overline{E}_{mu6}$=76,27716 mV²s) and variance and standard deviation, respectively, by 1.905 and 1.3803 times. With increasing of axial load on the friction pair to 750 N, i.e. increasing by 2.5 times, there is increase of $\overline{E}_{mu7}$ by 1.4297 times ($\overline{E}_{mu7}$ = 99.86224 mV²s). In this case, variance and standard deviation are increased, respectively, by 3.357 times and 1.832 times. From these data it is clear that increasing of axial load on the friction pair leads to a rapid increase in the median of average energy of resulting AE signals.

Similar results were obtained in the processing of resultant AE signals of total energy, as shown in Fig. 4. If the value of axial load is up to 300 N the median of total energy (average level of total energy) of the resultant AE signal is $\overline{E}_{ms3}$ = 72805.94978 mV²s, and variance and standard deviation, respectively, are: D_{Es3} = 1,05618·10⁹ mV⁴s² and σ_{Es3} = 32,498.904 mV²s. Increasing axial load on the friction pair to 450 N, i.e. by 1.5 times, there is increase by 1.0663 times ($\overline{E}_{ms4}$ = 77631.47132 mV²s). In this case variation D_{Es4} is increased by 1.129 times, and standard deviation σ_{Es4} by 1.062 times. Increase of axial load by 2 times, i.e. 600 H leads to increase by 1.155 times ($\overline{E}_{ms6}$ = 84135.7537 mV²s) and variance D_{Es6} and σ_{Es6} standard deviation, respectively, by 1.243 times and 1.115 times. Further increase of axial load on the friction pair to 750 N, i.e. increase by 2.5 times leads to increase by 1.47 times ($\overline{E}_{ms7}$ = 107,037.275 mV²s). In this case variance D_{Es7}, and standard deviation σ_{Es7} are increased, respectively, by 1.4549 and 2.11675 times.

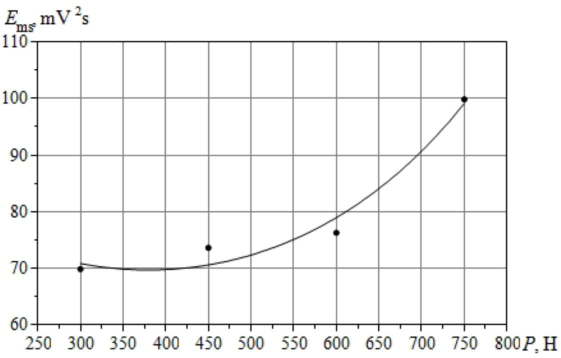
From these results it can be seen that with increasing of axial load on the friction pair relation of increase of total and average energy are almost equal. However, in respect of increase of standard deviations and variances for the median and average and total energy of the resulting signals AE differences are observed. For average energy detected acoustic radiation is greater than for total energy. At the same time, it should be noted that increase in medians dispersions of average AE energy with increasing of axial load on the friction pair slightly exceed their median value for total energy of resulting AE signals. In its turn, processing of experimental data [13] showed that more informative parameter of friction surfaces of composite materials is total energy of AE signals.

Dependence of median values of average and total energy, their variances and standard deviation with increasing of axial load on the friction pair is shown in Fig. 5 and Fig. 6. From Fig. 5 and Fig. 6. it is obvious that obtained dependences have non-linear increasing character. Analysis of the data showed that dependences of median changes of average and total energy of resulting AE signals, as well as their variance and standard deviation are described by power functions as follows

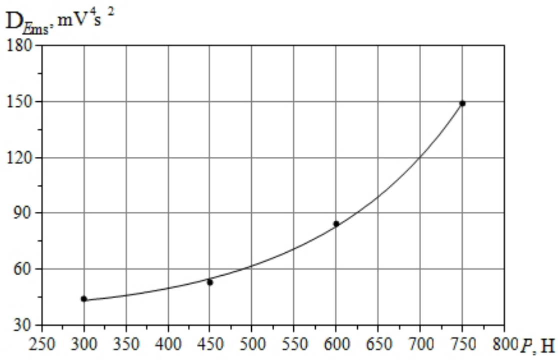
$$L = e^{a + bP + cP^2}, \qquad (3)$$

where L – analysed parameters of AE energy; P – axial load on the friction pair; a, b and c –coefficients of approximating expression.

Values of coefficients a, b and c of approximating expressions are equal to average energy medians - a =4,61428, b=-0,00195, c=2,5679·10⁻⁶; for variance of average energy medians – a=3,81806, b=-0,00131, c=3,857·10⁻⁶; for standard deviation of average energy medians - a=1,93612, b=-7,666·10⁻⁴, c=2,03·10⁻⁶; for total energy medians of AE signal - a =11,42133, b=-0,00134, c=2,068·10⁻⁶; for variance of total energy medians – a=21,48813, b=-0,00381, c=5,133·10⁻⁶; for standard deviation of total energy medians - a=10,714, b=-0,00177 and c=2,4366·10⁻⁶.



(a)



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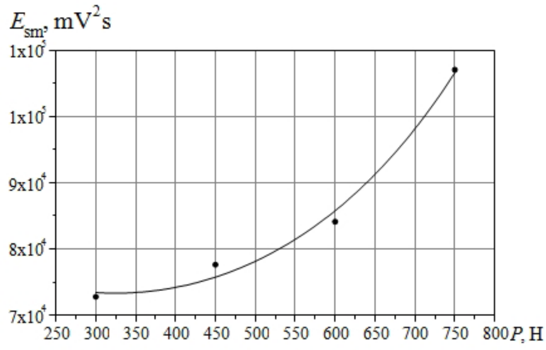

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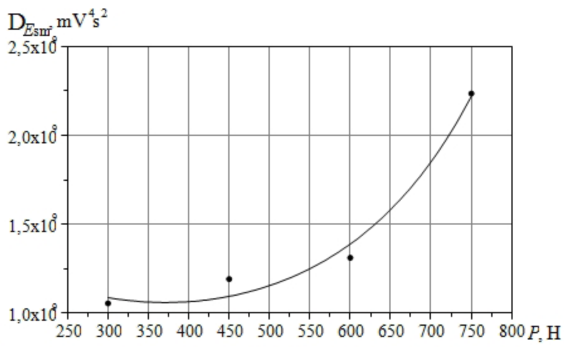

(d)

Figure 5. Graph of average (a) and total energy median values (c), averaged energy variation (b) and total energy variation (d) of resultant acoustic emission signals depending on axial load *P* on the friction pair

Thus obtained dependences (Fig. 5) are described by the expression (3) with adjusted determination coefficient R^2, the value of which is: for median of average energy - R^2=0.903; variation of average energy - R^2 = 0.997; for standard deviation of average median energy - R^2 = 0.995; for medians of total energy - R^2 = 0.97; variance of total energy - R^2 = 0.942; for standard deviation of total energy medians- R^2 = 0.923.

Conclusions

Results of experimental research showed that behaviour of average and total energy of resultant AE signals in time at changing of axial load at friction of pair and predetermined constant speed are similar. Registered AE signals have very rugged form. Statistical analysis of experimental data showed that distribution of average and total energy at a predetermined length of the sample and analysis of the specified range (equal to averaging time) with a probability of 0.95 are described by normal law distribution. Increasing of axial load on the friction pair increase of medians of average and total energy of resultant AE signals takes place, as well as increase in the values of variance and standard deviation. The ratio of increase in total and average energy is practically the same. However, increase in the variance of medians for average energy with increasing of axial load on the friction pair slightly exceeds their median values for total energy of the resulting signal AE. It shows their close sensitivity to the processes developing in the surface layers of the studied friction pairs, and the possibility of using these parameters as informative parameters.

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