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MODELLING OF ACOUSTIC EMISSION SIGNALS AT FRICTION OF MATERIALS' SURFACE LAYERS

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Abstract. A model of the signal of acoustic emission resulting from the normal wear of friction pairs is considered. Its mathematical description is obtained. Modelling of acoustic emission signals at varying strained/deformed state and rotation speed of initial friction pairs is done. The basic regularities of the transformation of acoustic emission form and those of its (emission) parameters of resulting signals are determined. Experimental research of acoustic emission signals is performed and proved to be good when compared to the results of theoretical research.

Keywords: acoustic emission signal, wear, friction, the surface of frictional contact, modelling, plastic deformation, fragile distraction.

1. Introduction

A significant amount of research has been performed on acoustic emission signals (AE) resulting from friction between the surface layer of different materials (Harvey *et al.* 2002, Wang *et al.* 2003, Babak *et al.* 2004, Babak *et al.* 2006, Фадин 1997, Фадин и др. 2001).

The results obtained show that, unlike static types of material loading, the processes of acoustic emission are registered as a continuous signal having a rather complicated structure. That is why the basic tendency of research lies in the search for the empirical dependence of varying parameters of AE signals on either loading characteristics or parameters of friction surface wear. At the same time, considerable difficulties in the description of signals, especially from the position of physical presentation of forming their processes, make it difficult not only to set up the experiments, but also to search for the parameters having the information about the processes flowing within the surface layers of friction units.

The approaches applied to static tests are usually used in the description of AE signals during dynamic loading. The basic one is the presentation of AE signal as a stochastic model (D'Attelis *et al.* 1992, Акустические … 1987, Иванов и др. 1981, Bukhalo *et al.*…2000, Lypez Pumarega *et al.* 1999, Lei X., *et al.* 2000, Lei *et al.* 2004, Houle *et al.* 1996, Minozzi *et al.* 2003, Majeed *et al.*). Not the physical process and the reasons for its appearance, but a signal when received by an exit signaller are meant. What is also meant is that the signal is the result of a great amount of some events occurring within the material and that each of the events occurs during a short period of time. In this case, the resulting signal is presented as the sum of the flow of instant impulse signals, which has the following appearance:

$$U(t) = \sum_i A_i F_i (t - t_i)$$

or $U(t) = \sum_i A_i F_i (t - t_i) + \sum_j G_j f_j (t - t_j^*) + S(t) + \lambda(t)$, here U(t) is the sum of instant impulse signals in volts; A_i is the random amplitude of a single impulse that appears at a random moment of time t_i; F_i - *are* characteristics of impulse form; G_j *are* the amplitude of the impulse noise component that appears at moment t_j^*; f_j is the characteristic of the impulse noise component; $S(t)$ and $\lambda(t)$ are correspondingly sinusoidal and arbitrary constant noise components, $S(t) = S_0 \sin(\omega t)$, S_0 is amplitude; and ω is frequency. It is taken that the value of the signal form $F_i(t)$ is known. What is meant is that it looks like:

$$F(t) = \sum_{k=1}^{m} e^{-t/\tau_k} \sin(2\pi f_k t),$$

if $t \geq 0$, and 0, if $t < 0$ here f_k is the frequency of the resonance signaler; τ_k *are* time shade characteristics and looks like $F(t) = \alpha_0 e^{-\beta t}$, here α_0 is initial amplitude; and β is shade coefficient (D'Attelis *et al.* 1992, Lypez Pumarega *et al.* 1999). There are also other depictions of the signal shapes, the choice of which is based on the results of experiments (Фадин *и др.* 2001, Majeed *et al.* 2001). The impulse flow is considered to be described with the help of the Poisson's Law.

While the result signal processing a certain limit is introduced, it provides the transfer from the continuous signal to the impulse one. In this case the notion of the following parameters is used: density of amplitudes of probability A_i, length ($\tau_i = t_i - t_{i-1}$), average values $\overline{A}_i$, $\overline{A}_i^2$, $\overline{\tau}_i$, and either spectral densities or correlation functions. Moreover, AE information is characterized by amplitude distribution, entropy, summary number of signals, and other parameters. If one does not use the limit, then one may determine the density of the average amplitude values of probability and correlation function of the resulting process. In fact, the stochastic approach supposes the determination of a certain amount of statistic parameters, altering the values of which may characterize change in the processes flowing within the materials. Approaches like that are attempts to ***DETERMINE*** the AE informative parameters. However, they do not allow one to establish or describe the regularity of its change depending on the mechanisms of the flowing processes and the conditions of their development.

The modelling and the basic regularities of parameters change determination of the AE signals will be held at the state of the normal wear.

2. Theoretical aspect

According to the work of V. Babak *models of AE signals* emitted at the secondary structures of *destruction types I and II* are developed at the normal wear (Бабак *и др.* 2007).

The models were formed for a tribosystem that has a kinematical sample scheme that looks like rollers (Fig 1). The surface of frictional contact is bounded by surface S, which looks like a thin line. It was considered that the contact surfaces are worked together. The material of the samples with the surface of contact interaction *S* (Fig 1) is isotropic, except the small area S_T, which is not familiar and is located within the *S* area. The area of non-familiarity S_T is much less than *S*, $S_T << S$. Considering the destruction processes in the S_{Tv} area and the destruction of the secondary structures of ***DESTRUCTION TYPES I AND II***, we were able to obtain mathematical expressions for the resulting AE signals *over* time. For the secondary structure of ***TYPE II DESTRUCTION*** (fragile destruction)

$$U_T(t) = U_0 \delta_0 \sigma_{0e}^3 e^{4zt} e^{-b\sigma_{0e} e^{zt}}, \qquad (1)$$

here $U_0 = kN_0 cz$ is maximal possible displacement at the destruction without the dispersive surface layer of material S_T; *k* is the coefficient of proportionality; N_o is the number of simple volumes in the area of non-familiarity S_T; *c* and *b* are coefficients of distribution of elementary volumes taking strength as the parameter (depending on the physical and mechanical characteristics of the material); σ_{0e} is the initial equivalent of strain at the stage of normal wear; t is time; $z = E/\xi$; ξ is the viscosity coefficient; E is the module of elasticity; $\delta_0 = \int_{t-\delta/2}^{t+\delta/2} a(\tau)d\tau$ is the average continuity of amplitudes at elementary volume destruction; and α (τ) is the function that determines the form of a single impulse of amplitudes (it is equal for all kinds of elementary volumes).

The equation is obtained by considering the dependence of one-cycle amplitude on the value of elementary volume strength in the area S_T.

For the secondary system of the type I (plastic deformation):

$$U_d(t) = U_{0d}\varepsilon_{0d}e^{rt}e^{-B\varepsilon_{0d}e^{rt}} , \quad (2)$$

here $U_{0d} = a_0 M \dfrac{\upsilon_d}{\ell_0}\delta_d$ is displacement amplitude that depends on the physical and mechanical characteristics of the material; a_o is amplitude of single impulse displacement at the dislocation movement(it is constant and does not depend on deformation); ℓ_o is the distance between two acts of emission of single dislocation; υ_d is the average speed of the dislocation movement (and is considered to be constant); ε_{0d} is relative initial deformation; $\delta_d = \int_{t-\delta_1/2}^{t+\delta_1/2} a_1(\tau)d\tau$ is the average continuity of the implying impulse; $a_1(\tau)$ is the function that determines the implying impulse form (is constant); and M , B, and r are the constants (which depend on the physical and mechanical characteristics of the materials).

The modelling of AE signals according to points (1) and (2) showed that with the increase in the initial level of equivalent tension (σ_{0e}), a decrease in time and increase in amplitude of the AE signal occurs.

The increase in the level of initial deformations (ε_{0d}) results in the time decrease in the AE signal without changing its amplitude. The further modelling of the AE signals occurred under the condition that destruction of the secondary structures of the I and II orders can follow any way consequently with rather small periods of time. The data obtained showed that the resulting signal contained amplitude drops along with consequent increase in its continuity.

The processes of forming the AE signals and modelling them occurred under the condition that the destruction of the secondary surfaces of types I and II for the selected kinematical scheme occurs within one area of frictional contact interaction, which looks like area S as a line having some width (Fig 1). In the area, it is considered that the secondary structures of type I and II may exist together. And their destruction processes may occur either consequently, or with a rather small period of time between them. At an end of the processes, a final AE signal occurs, which is shown in Babak's research work (Babak *et al.* 2007).

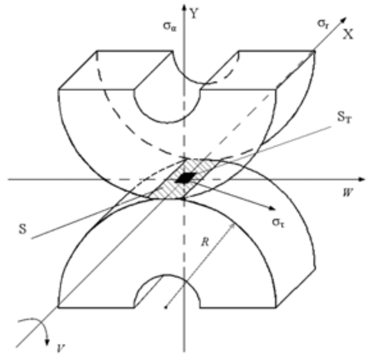

Fig 1. Scheme for the design of the model of AE signals: S is the area of frictional contact interaction of the "roller-roller" friction pair; S_T is the area of non familiarity in the area of contact interaction S; $\sigma_r = \sigma_н$ are radial strains; σ_τ is tangential strain; σ_a is axial strain; R is sample radius; and V is speed of rotation

Under the real conditions a consequent change in contact grounds occurs along the forming friction surfaces of the samples. In this case, the destruction of the secondary structures of types I and II occurs within consequently changing contact grounds. The time will depend on the speed of friction change pairs grounds, i.e. on the speed of the samples rotation, taking into account the final width of the contact area. At existence of the secondary structures of the I and II kinds being destroyed within the contact area, as well as the presence of dynamic load being replaced along with the contact areas in decreased time period, results in the fact that the impulse AE signals will be covered not only within the contact area, but also at passing from a ground to a ground. In other words, with the decrease of time of destruction of the secondary structures of the I and II kinds appearance (with the increase of the destruction activity), a transfer from the resulting impulse process of the AE signals emission to the continuous one will take place.

Everything considered above allows us to represent the AE signal as the sum of signals appearing at destruction of type I and II secondary structures in random periods of time, i.e:

$$U'(t) = \sum_i U_T(t - t_i) + \sum_j U_d(t - t_j) , \quad (3)$$

here t_i, t_j are random moments of AE signal appearance $U_T(t)$ and $U_d(t)$ at the destruction of the secondary structures of type I and II correspondingly.

Keeping (1) and (2) in mind, we can see that expression (3) will look like

$$U'(t) = \sum_i U_0\delta_0\sigma_{0e}^3 e^{4z(t-t_i)}e^{-b\sigma_{0e}e^{z(t-t_i)}} +$$

$$\sum_j U_{0d}\varepsilon_{0d}e^{r(t-t_j)}e^{-B\varepsilon_{0d}e^{r(t-t_j)}} . \quad (4)$$

The (4) makes it possible to see that under the correct initial conditions (the given physical and mechanical characteristics of the materials of the friction pair at the constant contact area) the resulting AE signal is determined by the initial strained and deformed state (σ_{0e}, ε_{0d}) and the time of the start of destruction of the secondary structures of types I and II is (t_i, t_j). Based on this, the modelling of the AE signals was held; it followed (4), and had two stages. In the first stage, the change in the resulting AE signal depending on the starting point for the destruction of the secondary structures of types I and II at constant meanings of σ_{0e}, ε_{0d} was researched. In the second stage the change of the resulting AE signal depending on change of σ_{0e}, ε_{0d} at the constant time of the secondary structures of types I and II was researched. The results of such modelling, which looked like the graphs of change $\tilde{U}(t) = U'(t)/U_{\max}$ in relative values are depicted in figures 2 and 3. At the graphs' time is established to be enough for the action of the load over the friction couple and is equal to $t_{\max}$. The parameters σ_{0e}, ε_{0d}, b and B are drawn to the non-measured values.

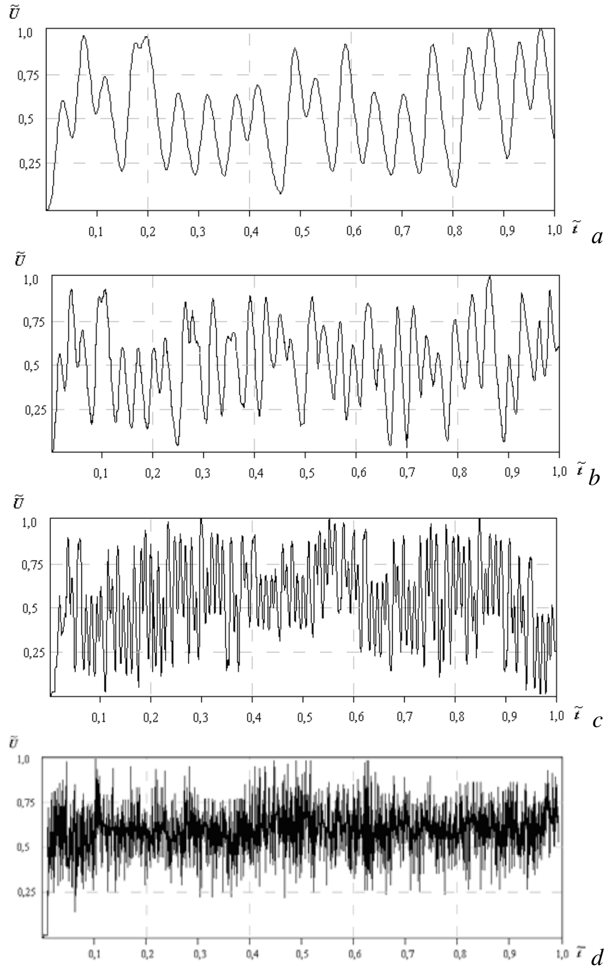

Fig 2. The forms of the AE signals at the stage of normal wear at various initial times of destruction of secondary structures of types I and II: $\sigma_{0e} = 17$; $\varepsilon_{0d} = 17$; $b = B = 10$. $\tilde{U}$ is the normal meaning for $U_{\max}$, and $\tilde{t}$ is the normal one for $t_{\max} = const$. The time step of destruction of every following structure of either type I or II in relative units: *a* – 0,0007; *b* – 0,0004; *c* – 0,0001; *d* – 0,00001

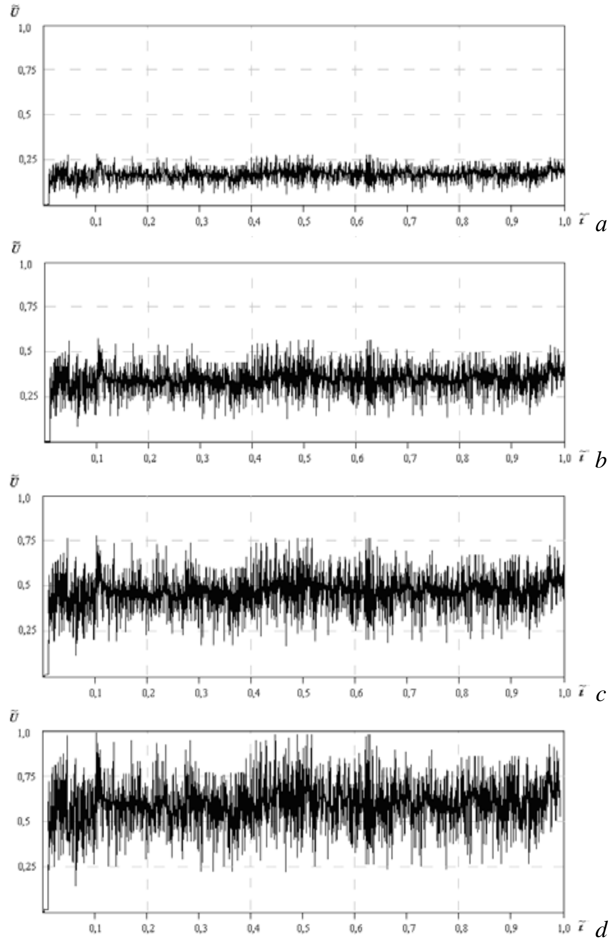

Fig 3. Forms of AE signals at the stage of normal wear at the destruction of the secondary structures of types I and II for various initial values of strains and deformations: $b = B = 10$. The step of added start time of every following structure of either type I or II is equal to 0.00001 in relative units. $\tilde{U}$ is the normal value for $U_{\max}$. $\tilde{t}$ is the normal value for $t_{\max} = const$. The values of the initial tensions and deformations are the following: *a* – $\sigma_{0e} = 11$; $\varepsilon_{0d} = 11$; *b* – $\sigma_{0e} = 13$; $\varepsilon_{0d} = 13$; *c* – $\sigma_{0e} = 15$; $\varepsilon_{0d} = 15$; *d*– $\sigma_{0e} = 17$; $\varepsilon_{0d} = 17$.

In the first stage of the modelling of AE signals, it was accepted that $\sigma_{0e} = 17$, $\varepsilon_{0d} = 17$, $b = B$, $b = B = 10$. And the resulting signal, according to (4), was formed at the consequent interchanging of the structures of types I and II according to a certain scheme that did not change in the following stages of modelling. A step occupies *at* the time of start of destruction of the every following secondary structure of types I and II varies from 0.0007 till 0.00001 relative units. And the time between the start of the destruction of structures of types I and II did not change with the stage development.

In the second stage of AE signals modelling, it was accepted that $b = B = 10$. The resulting signal according to (4) was formed at the consequent interchange of destruction of the structures of types I and II according to a certain specially selected scheme that did not change in the following stages of modelling. The step of start time point of destruction following *each other structure* of either I or II type did not change with the any following stage and was equal to 0.00001 relative units. The values σ_{0e} and ε_{0d} changed from 11 to 17 with the additional step equal to 2.

From the results obtained, one can see that at the consequent destruction of the secondary structures of types I and II with rather small time intervals the resulting AE signal looks like a continuous one (Figs 2, 3). In other words, the AE impulse signals formed during the separate destruction of the structures of types I and II are transformed into a continuous AE signal that appears during the consequent destruction of the secondary structures of types I and II with arbitrary starting times (Бабак *и др.* 2007). Meanwhile, with the decrease in the initial time of destruction of the secondary structures of types I and II, a compression of the signal over time and a transformation of its form occur and it starts to look like a hilled signal with amplitude drops (Fig 2). According to the research results, at the given initial tensions and deformations the amplitude of the AE impulse signal at the destruction of the secondary structure of type II exceeds the amplitude of the AE signal of the secondary kind of type I (Бабак *и др.* 2007). This demonstrates that the amplitude drops will be determined by the destruction of the secondary structures of type II.

This if proved by the results obtained at the second stage of modelling, when the initial tension and the deformation were changed (Fig 3). As we can see from figure 3, at constant initial start time step of the destruction of the secondary structures of types I and II with the given constant scheme, the increase in the initial tensions and deformations results not only to the increase of the average amplitude level of the resulting AE signal, but also to the increase in the arbitrariness of the position along the amplitude (the difference between the maximal and the minimal values of the amplitude drops). Such a result can be explained in the following way. When differences in the amplitude of the AE signals appear, the signals are formed during the process of destruction of the secondary surfaces of types I and II, the upper layer of the resulting AE signal amplitude will be influenced by the amplitude of the signal of the secondary structure of type II, and the lower one will be influenced by that of type I. At minimal initial tensions and deformations of AE signals, amplitudes at the destruction of the secondary structures of types I and II do not differ widely. At the imposing an input of the signals at the destruction of the secondary structures of type I into the resulting signal that will be commensurable with the input of the signals appearing at the destruction of the structures of type II. Under the given conditions, it is obvious that the amplitude dispersion of the resulting signal is minimal, which is observed in the modelling results (Fig 3,*a*). With the increase in the initial tensions and deformations, the difference within the amplitude of AE signals for the structures of types I and II increases. (Бабак *и др.* 2007). This signal having appeared at the destruction of the secondary structure of type I, under the conditions mentioned above, the input into the resulting AE signal of the signal amplitude, and, decreases. This, surely, must result in the decrease of the lower layer of the resulting signal, and, as the result, to the increase in the dispersion of the medium level and the amplitude of the AE signal, which is observed in the results of the modelling (Fig 3).

3. Experimental research

The experimental research of the AE signals took place with the friction machine of CMT-1 type at the friction of the steel 12X2H4A examples. A “roller-roller” (“disc-disc”) kinematical scheme has been used. The gear lubricant Б-3В was used for lubrication. The choice of the sample materials for the friction couples and the choice of lubricant was made because of their wide application in the transmissions of aviation gas-turbine engines (GTE).

In correspondence with the kinematical scheme selected, one of the samples of the friction couple has less rotation speed than the other one, which was rotating on a spindle of the CMT-1 machine (Fig 4,*A,B*). The regimen of rolling friction was used at the same time, considering 20 % slippage. The dimensions of the samples were the following: diameter D = 25 mm, thickness h = 15 mm. The rotation speed of the shaft of the friction machine was V = 500 rot/min (Fig 4,1). Its value was selected according to the maximum approach to the conditions of exploitation of the dots of friction being modelled. The working tensions of the contact interaction of the friction couple σ_P were changed in the diapason of values within 400 MPa and 1000 MPa at increments of 200 MPa. The increase in working tensions occurred at the stage of normal wear, i.e. after the completion of run-in of the friction pair.

The time of the initial addition of the friction couple was 20–25 minutes. The time of the secondary addition after the increase in working tensions was 4–5 minutes. At each exploitation load, the friction couple worked five hours.

A piezoceramic signaller was installed on the immovable sample of the frictional couple, this signaller being intended for the registration of the AE signals (Fig 4,2). The output signal was amplified by the preliminary amplifier 3 and was passed to the AE diagnostic complex 4 (AEDC). The AEDC is a mobile computer with program software that allows the processor of measurements to be controlled and the parameters of the AE signals to be processed. It also presents the results of analysis as a table or graph (Fig 4,PS). The AEDC allows the following AE signals parameters to be processed: average amplitude, energy, and power; summary energy; and the collected values of parameters. Moreover, It also creates a graphic graphic presentation of the initial AE signal and and analyzes its parameters. The additional parameters researched include the friction moment, which was measured with the help of the friction moment measurer (Fig 4,5).

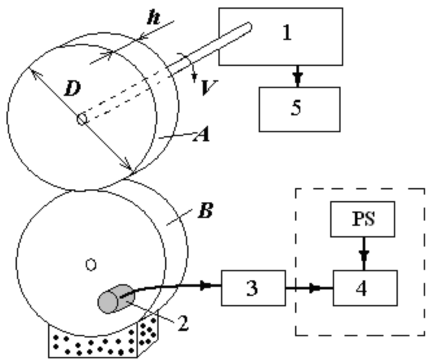

Fig 4. Method of AE signal research for the friction pair as the kinematical scheme "roller-roller" ("disc-disc"): A is movable sample; B is "immovable" sample; *D* and *h* are sample diameter and sample thickness correspondingly; *V* is speed of rotation of movable sample; 1 is universal friction machine CMT-1; 2 is AE signaller; 3 is preliminary amplifier; 4 is mobile computer; 5 is friction moment measurer; and PS is the program software

Typical results of the registration of AE signals at a change in the rotation speed of the frictional pair and at constant value of the working contact tension σ_P at the stage of normal wear of the friction pair are shown in figure 5. The value of σ_P was 1000 MPa.

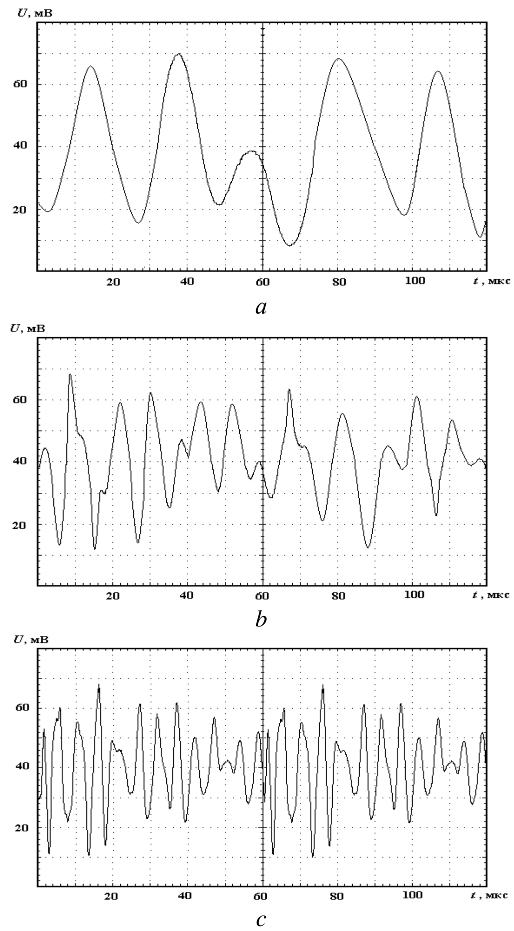

Fig 5. AE signals registered at the stage of normal wear at constant working contact tension σ_P and at varying rotation speed of the friction pair: *a* – *V* = 200 rot/min; *b* – *V* = 500 rot/min; *c* – *V* = 800 rot/min. Working contact stress σ_P = 1000 MPa

Figure 6 shows the typical results of the registration of the AE signal at constant speed of the friction pair rotation and change in values of the working contact tension σ_P at the stage of normal wear. The value of the rotation speed was equal to 500 rpt/min. Figure 5 shows that the registered AE signals are constant signals and have a complicated cut form. With the increase in the rotation speed of the movable sample of the friction couple from 200 rot/min to 800 rot/min and unchanging value of the working contact tension σ_P, the transformation of the form of the AE signal and its time compression are observed. Such a change in the character of the AE signal can be explained by the positions of the modelling held. The increase in the speed of the rotation of the frictional pair really corresponds to the decrease in time between the changes of the contact grounds and thus results in the reduction in time between the consequent acts of destruction. According to the modelling held in figure 2, it must result in the compression of the AE signal in time.

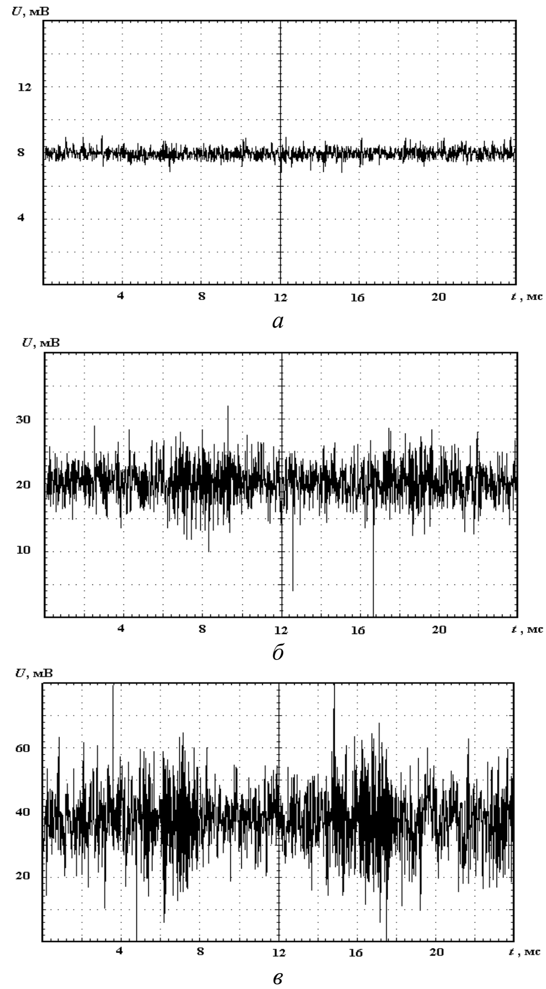

Fig 6. AE signals registered at increase in working contact tensions σ_P at the stage of the normal wear of the friction couple: *а* - σ_P = 400 MPa; *б* - σ_P = 800 MPA; *в* - σ_P = 1000 MPa. The speed of rotation of the friction pair is *V* = 500 rot/min

At the same time as it can be seen from the figure 6, when working contact tensions σ_P change and rotation speed of the movable sample of friction pair, the registered AE signals have a complicated hilled form as well. Along with this, with the increase in σ_P from 400 MPA to 800 MPA and 1000 MPA, not only is an increase in average value of the amplitude of the AE signal observed, but also an increase in the maximum and minimum values (dispersion) along the amplitude can be seen. Such a change of the parameters of the AE signals also accurately corresponds to the results of the modelling held (Fig 3).

4. Conclusion

At the result of the research held, a model of resulting AE signal is been developed, the it is being formed at the stage of normal wear of friction pair. A model was built on the basis of information already existing about the normal wear process, connected with the destruction of the secondary structures of types I and II. It is also shown that AE impulse signals formed during the separate destruction of the structures of types I and II are transformed into a continuous AE signal that appears during sequent destruction of the secondary structures of types I and II with an arbitrary initial time.

The resulting signal has a complicated form, the change of view and transformation of which are caused by the differences in the parameters of the impulse AE signals formed during the destruction of the structures of types I and II during the work of the friction pair. In accordance with the modelling it was established that at constant initial stresses and deformations, at increasing the speed of rotation, at the stage of normal wear, decrease time between the start of distraction of the structures of types I and II. It results in the compression of the AE signal over time and its transformation into a signal with a hilled shape.

At the constant speed of friction pair rotation, the increase in the initial stress and deformation at the stage of normal wear results in the increase in the average level of the resulting AE signal and to the increase in its amplitude dispersion. The forms of AE signals registered during experimental research applied to the forms of AE signals that were obtained during theoretical research.

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MEDŽIAGŲ PAVIRŠIAUS TRINTIES AKUSTINĖS EMISIJOS SIGNALŲ MODELIAVIMAS

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S a n t r a u k a

Išnagrinėtas akustinės emisijos signalų, kurie susidaro normaliame besitrinančių porų dilime, modelis ir jis matematiškai aprašytas. Atliktas akustinės emisijos signalų modeliavimas esant įvairiam pradinių trinties porų sukimosi greičiui ir įtempimų/deformacijų būsenai. Nustatyti pagrindiniai akustinės emisijos signalų formos ir parametrų transformacijos dėsningumai. Atliktas eksperimentinis akustinės emisijos signalų tyrimas, kurio rezultatai gerai sutapo su teoriniais.

Reikšminiai žodžiai: akustinės emisijos signalas, dilimas, trintis, trinties kontakto paviršius, modeliavimas, plastinė deformacija.