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INFLUENCE OF FRICTION SURFACES PROPERTIES OF COMPOSITE MATERIALS ON ACOUSTIC EMISSION

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Abstract. *The simulation of amplitude and energy of acoustic emission resulting signals at friction of composite materials surfaces layers was conducted. The regularities of changes in the amplitude and energy parameters of acoustic emission resulting signals which are depending from hardness of composite materials surfaces layers were determined. The description of regularities of changes with their statistical estimates was conducted.*

Keywords: acoustic emission, amplitude, composite material, energy, friction, law, level, parameter, signal, variation.

1. Introduction

Composite materials (CM) and coatings based on them are widely used in friction units. The increasing of friction surfaces layers wear resistance with CM (Bria et al. 2011; Koutsomichalis et al. 2009; Takeshi et al. 2009) leads to decreasing of friction unit wear and increasing their service life. The main characteristics at the control and research of CM friction units (Basu et al. 2005; Hong et al. 2011; Reddappa et al. 2011) are: coefficient of friction, friction force and friction moment, the temperature in the area of frictional contact, substance of wear particles and other. However, at practice, a group of these parameters are useful in research of processes which are developing at catastrophic wear of frictional contact surfaces layers.

In recent years for monitoring and diagnosis of friction units are increasingly using Acoustic Emission (AE) method due to it high sensitivity to the processes that occurs in frictional contact. It should be noted that this method is used for both traditional and CM (Benabdallah, Aguilar 2008; Fan et al. 2010; Hase et al. 2009).

However, significant complexity, which is connected with formation of acoustic radiation, as well as the interpretation of the information significantly limits the usage of AE method in monitoring and diagnosis of friction units with CM.

From this point of view is particularly important theoretical research of acoustic radiation processes and particularly the definition and description of the laws of changes of AE signals parameters during the processes development which are occurring at sliding contact of friction units. In this case, the important task is to determine the influence of various factors on the processes development of the CM destruction and, respectively, formed AE signals. Its solution will be interpret acoustic radiation, determine the informative parameters of AE signals, and laws of their changes. These theoretical researches are the basis for the development of new methods of control and diagnostics of friction units with CM.

2. Analysis of sources and publications

Theoretical studies of acoustic radiation at friction and wear of friction units with traditional materials were considered in (Filonenko, Stadnychenko et al. 2008; Filonenko, Stakhova et al. 2008). Was developed the model which is based on the formation of the resulting acoustic radiation at destruction of the secondary structures of I and II type, and was received analytical expression that describe the AE resulting signal at influencing of various factors. Simulation results of formed AE signals provided the laws of changing of their parameters at normal wear and at the stage of catastrophic wear. It should be noted that the simulation results of AE signals showed good agreement with results of experimental research. The developed model of AE signals can be used only at friction of materials with crystal (traditional) lattice.

At research of the physical basis of the CM destruction is widely used concept of “Fibre Bundle Model” (FBM) (Raischel et al. 2005; Shcherbakov 2002). Theoretical studies of the formation of AE signals at destruction of CM at unaxial tension were considered in (Filonenko et al. 2010; Filonenko et al. 2009).

The model of formation AE supposed destruction of CM elements, and thermally activated mechanism of their failure. It should be noted that the developed model can be applicable only for uniaxial tension. At the same time, at friction of surfaces layers is forming more complex type of loading, which can be presented in the form of shear load. In (Filonenko et al. 2010), with using concept of FBM and the kinetics of the destruction process, was received analytical expression for AE signal which formed at CM destruction under shear load.

It was considered that the CM sample consists from elements with same size. Elements evenly distributed in the volume of the sample. It was assumed that the matrix does not affect on loss of CM capacity. Was considered that destruction of the elements in the sample had consistent manner. The external load is distributed evenly on the remaining elements that had the same increased axial deformation. Also was conducted that destruction of CM elements occur according to rule "OR", i.e. due bending and stretching then deformation reach certain threshold. Bending and stretching can be independent or interrelated with some expression. Under such conditions, taking into account the general expression for stress change in the elements for the case of independent uniform distributions of threshold levels with the boundaries of [0, 1], was obtained an expression that describes formed AE signal

$$U(t)=U_0\upsilon_0[\alpha t(1-\alpha t)(1-g\sqrt{\alpha t})-\alpha t_0(1-\alpha t_0)(1-g\sqrt{\alpha t_0})]\times$$
$$\times e^{r[\alpha t(1-\alpha t)(1-g\sqrt{\alpha t})-\alpha t_0(1-\alpha t_0)(1-g\sqrt{\alpha t_0})]}\times \qquad ,$$
$$\times e^{-\upsilon_0\int\limits_{t_0}^{t} e^{r[\alpha t(1-\alpha t)(1-g\sqrt{\alpha t})-\alpha t_0(1-\alpha t_0)(1-g\sqrt{\alpha t_0})]}dt} \tag{1}$$

where U_0 – maximal possible displacement in case of instantaneous destruction of CM pattern:

$U_0 = N_0\beta\delta_S$;

N_0 – initial number of CM elements;

β – coefficient of proportionality;

δ_S – parameter which defines the form of excitation impulse at destruction of unit element (take on dimension of time).

υ_0, r –constants, which depend on the physic-mechanical characteristics of the CM;

α – speed of load;

t, t_0 – respectively, current time and time that corresponds to beginning of the elements destruction;

g – coefficient, which depends on the geometrical sizes of the fiber (area of cross-section and length).

Equation (1) describes the AE signal, which is formed at destruction of elements with specified size. This allows to obtain the laws of AE parameters change at the affecting of such factors as the speed of loading, physical and mechanical characteristics of the CM elements, the size of its elements, dispersion properties, strength and others. As noted in (Raischel et al. 2005), the concept of FBM can be used as simple model at consideration of friction units surfaces layers with CM. In this case, the elements of CM can be viewed as projections on the frictional contact surface which are destructing under shear load. Accordingly, the obtained research results in (Filonenko et al. 2010) can be useful for model development of AE resulting signal, which is formed at friction and wear of CM surfaces layers.

3. Formulation of article objectives

In this paper we consider a model of resulting AE signal formation at friction of surfaces layers with CM. There will be simulation of resulting AE signal at influencing of some factors.

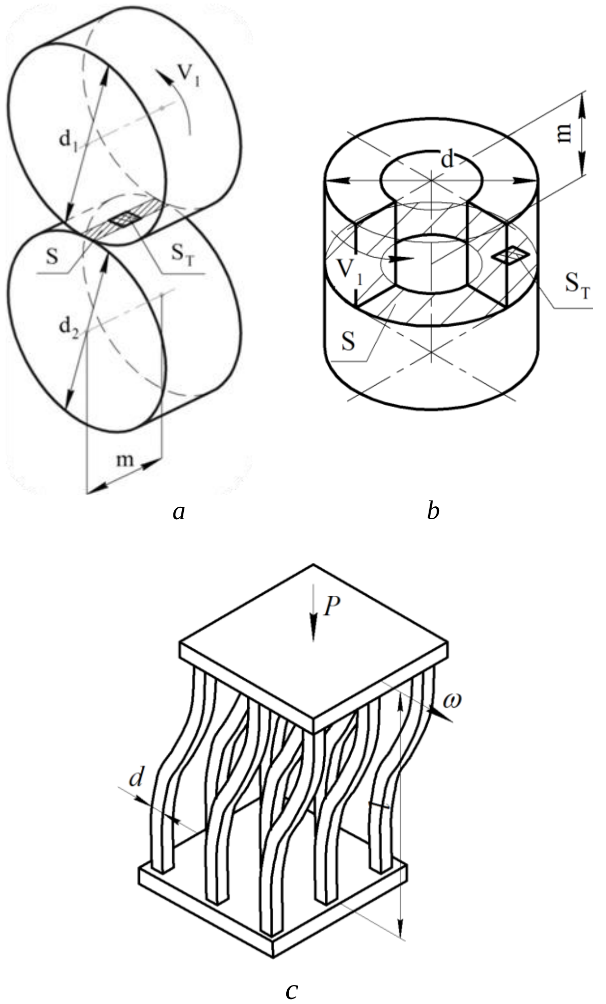
We simulated the resulting AE signals in time, which were formed at friction of CM surfaces layers and which depended from physical and mechanical characteristics of its projections. Will be conducted analysis of the amplitude and energy parameters of formed AE signals and also the definition of the laws of their changes at parameter change υ_0 which order of value is comparable with the period of the lattice oscillations of solids which is sensitive to the physical-mechanical nature and structure of the solid.

4. Results of researches

Suppose that we have CM friction units with different types of interaction surfaces (Fig. 1, *a*, *b*).

Surface frictional contact in the friction area is bounded by *S*. We assume that the junction surface layers in the area of *S* consist from projections, which were presented CM elements (Fig. 1, c). At considering of elements destruction in the area *S*, we take the same initial conditions as in (Filonenko et al. 2010): the quantity of elements in the conjugation is N_0; elements are evenly distributed over the surfaces; elements have the same physical and mechanical properties. We assume that the matrix does not affect on the process of CM elements destruction. Pressure of contact surfaces (elements) provides constant perpendicular axial force *P*.

We accept the terms of the elements destruction in area *S* same as in (Filonenko et al. 2010). Suppose that for given value of *P* which applied to CM by shear load ω, the destruction of its elements starts at value of threshold equivalent stress σ_0.



a *b*

c

Fig. 1. Kinematic scheme of friction units with forms of rings (*a*) and rollers (*b*), also idealized scheme of elements destruction in contact area S_T (*c*):

V_1 – rotational velocity of patterns;
S – area of contact interaction;
S_T – area in contact surface;
d – size of composite material element side in surface layers contact;
P – axial load;
ω – shear load

Under such conditions, the destruction of CM elements in the area *S* of contact interaction will be accompanied by AE signal formation which was described by equation (1). We assumed that the friction unit was rotated with constant speed V_1. This provides continuous sequential change of areas contact interaction S_j, where *j* – quantities of areas. Then each subsequent destruction of area will lead to the formation of AE signal, which is also described by (1).

For such conditions, will be formed AE resulting signal which presented as sum of the formed signals at destruction of each subsequent area S_j

$$U_p(t) = \sum_j U_j(t - t_j), \tag{2}$$

where *j* – index number the *j*-th area of contact interaction (*j*=0, 1, 2,…..,*m*);

$U_j(t_j)$ – *j*-th AE impulse signal, which was formed on the *j*-th area of contact interaction and described by (1);

t_j – time of *j*-th AE signal appearance.

Moment of time then occur each subsequent AE signal can be written as

$$t_j = j\Delta t_j, \tag{3}$$

where Δt_j – the time interval between the beginning of the subsequent formation and previous AE impulse signal.

At constant speed of changes between areas of contact interaction and destruction of all elements in the area (Fig. 1, *a*, *b*) will be constant AE signals interval. In this case, all the AE impulse signals will be the same according to (3). If destructions of the elements occurs at variable area S_T (Fig. 1, *a*, *b*) in the area of contact interaction *S*, when depending on the location and size (quantity of elements N_0 in area S_T), the interval of time Δt_j will vary. In this case, the moment of time can be written as

$$t_j = j\,\Delta t_j \pm \delta, \tag{4}$$

where δ – random component at the moment of each subsequent AE signal occurrence.

In this case, the formed AE impulse signals will differ from each other – will be various parameters of AE signals. Obviously, the closest to the reality of change in contact interaction areas and destruction of elements in area S_T is to present the moment of AE signals time appearance in form of expression (4).

It should be noted that in the expression (1) was included parameter υ_0, which was sensitive to the physical and chemical nature and structure of the

CM solid. Certainly, the determination the effect of these characteristics of CM friction surfaces on the friction process character and change of amplitude and energy parameters of formed AE resulting signals is important, in terms of monitoring and diagnosing of friction units with CM.

Let's simulate the AE resulting signal, according to (2) with (4) at change of parameter values υ_0. Increasing the value of υ_0 characterizes greater tendency of the CM to brittle fracture. We assumed that the quantities of destructible elements N_0 at each area S_T (Fig. 1, *a*, *b*) was constant. Axial load *P* was constant, and the destruction of CM elements starts at a threshold stress of destruction σ_0. While friction unit is rotating the friction areas S_T can change own location in the area *S*. Under such conditions, the start of each subsequent contact interaction destruction (start time appearance of subsequent AE signal) according to (4) will be given in the form

$$\tilde{t}_j = \tilde{t}_0 + j\Delta\tilde{t}_j + \tilde{\delta} ,$$

where $\tilde{t}_0$ – destruction start of first area in contact interaction, which corresponds to the threshold destruction stress.

At simulation all parameters that included in the expression (1) were presented in relative units. We use the following parameters $\tilde{r}$, $\tilde{g}$ and $\tilde{\alpha}$: $\tilde{r}$ = 10000; $\tilde{g}$ =0,1, $\tilde{\alpha}$=200. Value $\Delta\tilde{t}_j$ was equal to $\Delta\tilde{t}_j$ =1,1×10^-6^. The value $\tilde{\delta}$ changed randomly. Destruction time of the CM elements $\tilde{t}_0$ and the threshold destruction stress $\tilde{\sigma}_0$ were assumed: $\tilde{t}_0$=0,006 and $\tilde{\sigma}_0$=0,101941909. Value $\tilde{t}_0$ and $\tilde{\sigma}_0$ were determined by the diagram of equivalent stresses in time for accepted parameters and specified speed of CM loading, according to (Filonenko et al. 2010). The value $\tilde{\upsilon}_0$ varied from $0{,}4\times10^{-6}$ to 1×10^{-6} with increment $\Delta\tilde{\upsilon}_0=0{,}2\times10^{-6}$. With increasing of values $\tilde{\upsilon}_0$ we proportionally decrease values of parameter $\tilde{\delta}$ in the range from 0 to $7{,}5\times10^{-7}$ and from 0 to 3×10^{-7}.

Theoretical calculation of the amplitude and the energy of the AE resulting signals with using expression (1), was not possible.

Therefore, their values, in accordance with definitions of parameters (Baskakov 2005), we calculated numerically.

The results of the modeling of AE resulting signal amplitude and the energy for the accepted boundary values $\tilde{\upsilon}_0$ are shown in Fig. 2 in relative units. Simulation parameters: $\tilde{\alpha}$=200; $\tilde{g}$=0,1; $\tilde{\sigma}_0$=0,101941909; $\tilde{r}$=10000; $\tilde{t}_0$=0,0006; $\Delta\tilde{t}_j=1{,}1\times10^{-6}$.

The AE resulting signal is continuous signal with strongly irregular form. AE signals are characterized by the mean value of the amplitude and energy, as well as the size of their spread.

From Fig. 2 we see that with increasing of values $\tilde{\upsilon}_0$ the character of the AE resulting signals was unchanged. AE signals are continuous signals with strongly irregular form. The results of the calculations the average amplitude $\bar{\tilde{U}}$ and the energy $\bar{\tilde{E}}$ of the resulting AE signal, and their dispersion $s^2_{\bar{\tilde{U}}}$ and $s^2_{\bar{\tilde{E}}}$ in relative units for each value $\tilde{\upsilon}_0$ are presented in the form of curves in Fig. 3, *a*.

At determining of amplitude and energy parameters of AE signals, the length of the sample, and the sample interval were unchanged and, therefore, were equal $t_d=1\times10^{-7}$ and *N*=3000 values of calculated amplitudes and energies.

Fig. 3, *a* shows that with increasing of parameter values $\tilde{\upsilon}_0$ occur non-linear drop in average level of the amplitude and the energy of AE resulting signals.

Thus the increasing of values $\tilde{\upsilon}_0$ in 1.5 times (from $0{,}4\times10^{-6}$ to $0{,}6\times10^{-6}$) values $\bar{\tilde{U}}$, $\bar{\tilde{E}}$, $s^2_{\bar{\tilde{U}}}$, $s^2_{\bar{\tilde{E}}}$ are decreasing, respectively, in 1,24, 1,58, 2,4 and 3,82 times. If $\tilde{\upsilon}_0$ increased in 2 times (from $0{,}4\times10^{-6}$ to $0{,}8\times10^{-6}$), then values $\bar{\tilde{U}}$, $\bar{\tilde{E}}$, $s^2_{\bar{\tilde{U}}}$, $s^2_{\bar{\tilde{E}}}$ were reduced in 1,45, 2,18, 3,69 and 9,16 times, respectively. With increase $\tilde{\upsilon}_0$ in 2,5 times the values $\bar{\tilde{U}}$, $\bar{\tilde{E}}$, $s^2_{\bar{\tilde{U}}}$, $s^2_{\bar{\tilde{E}}}$ were reduced in 1,66, 2,81, 3,87 and 13,63.

It should be note what the largest percent increment at change of values parameters $\tilde{\upsilon}_0$ have energy parameters of AE resulting signal (Fig. 3, *b*).

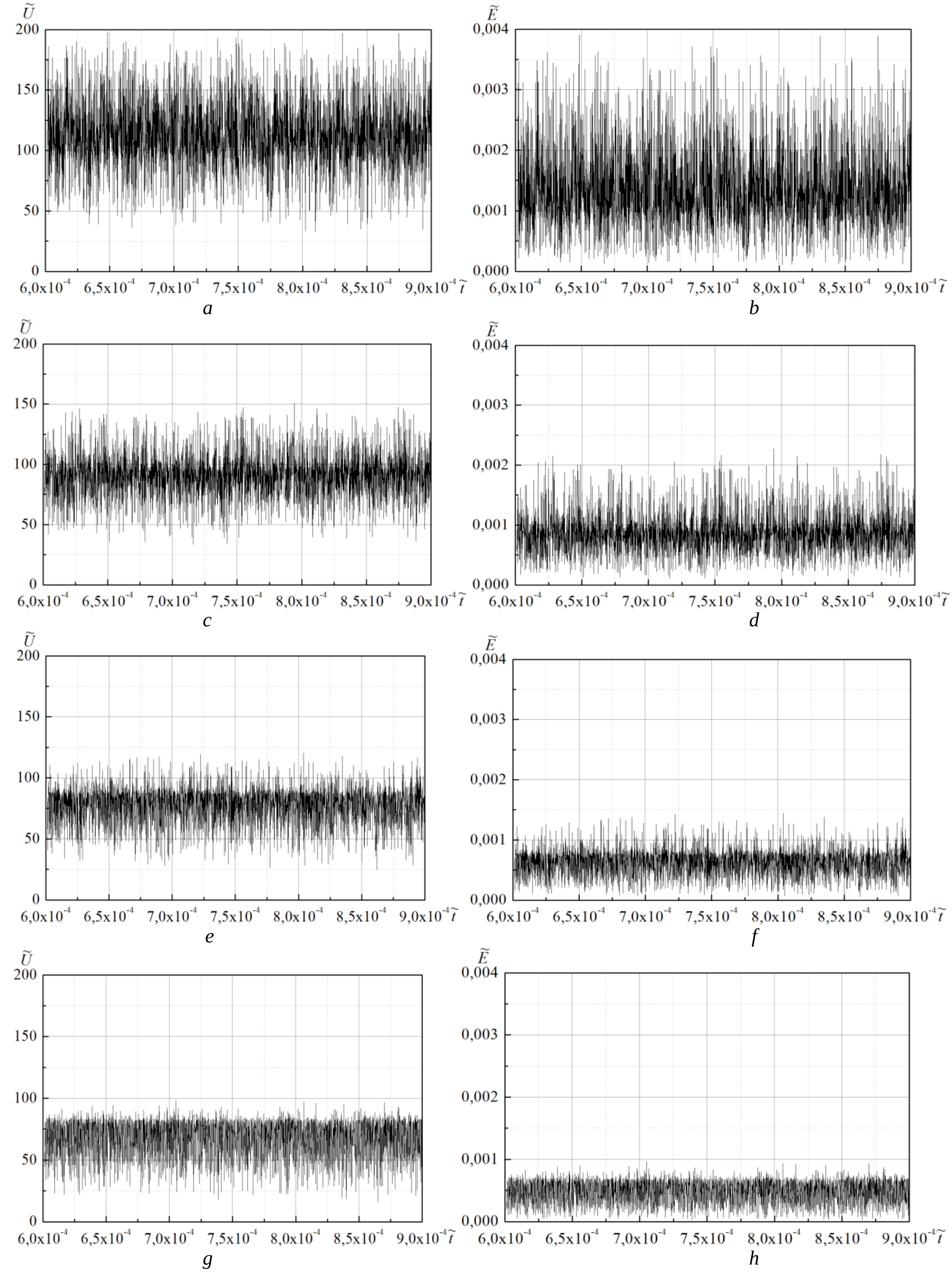
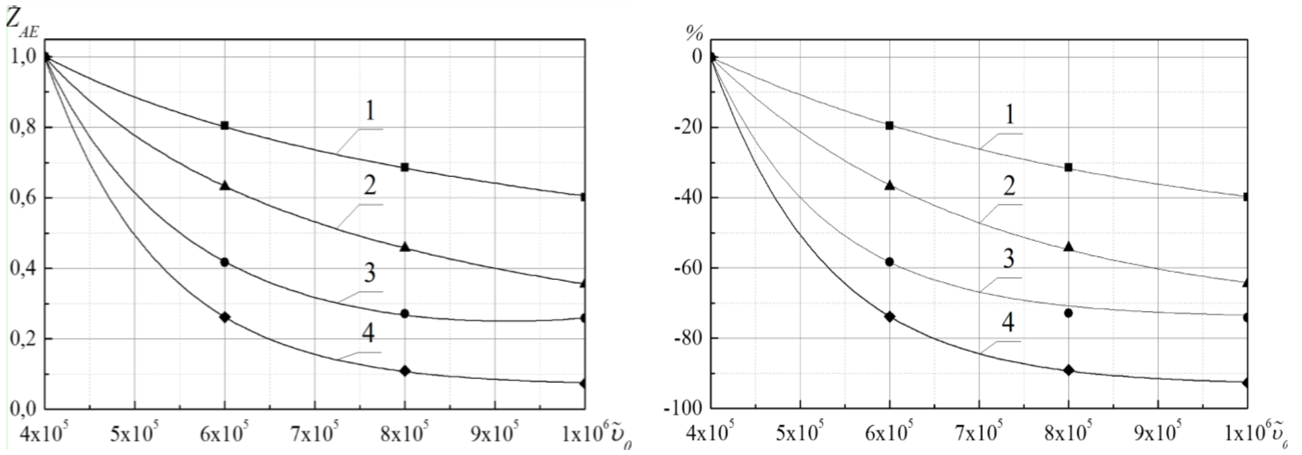


Fig. 2. Plots of amplitude (*a*, *c*, *e*, *g*) and energy (*b*, *d*, *f*, *h*) changes of the acoustic emission resulting signal in time, according to (2), in relative units at changing tendency of the CM friction surfaces to brittle fracture:
values of $\tilde{\upsilon}_0$: *a*, *b* – $\tilde{\upsilon}_0 = 0{,}4\times10^{-6}$; *c*, *d* – $\tilde{\upsilon}_0 = 0{,}6\times10^{-6}$; *e*, *f* – $\tilde{\upsilon}_0 = 0{,}8\times10^{-6}$; *g*, *h* – $\tilde{\upsilon}_0 = 1\times10^{-6}$;
values of $\tilde{\delta}$: *a*, *b* – $\tilde{\delta} = 0\ldots7{,}5\times10^{-7}$; *c*, *d* – $\tilde{\delta} = 0\ldots5\times10^{-7}$; *e*, *f* – $\tilde{\delta} = 0\ldots3{,}75\times10^{-7}$; *g*, *h* – $\tilde{\delta} = 0\ldots3\times10^{-7}$



a *b*

Fig. 3. Regularities of the change (*a*) and the percentage increment (*b*) of AE resulting signal parameters $\tilde{Z}_{AE}$ at change of parameter values $\tilde{\upsilon}_0$:

1 – average amplitude level;
2 – average energy level;
3 – variance of the average amplitude level;
4 – variance of the average energy level

The results of such researches also shows that the largest increment at changing values of $\tilde{\upsilon}_0$ have variance of average energy level of the AE resulting signal. Smallest increment of resulting AE signal parameters have average amplitude level.

Statistical analysis of the data show that the reliability of the regularities description of AE resulting signals amplitude and energy parameters change at changing CM tendency to brittle fracture were confirmed with probability for the average amplitude level, variance of the average amplitude level, average energy level and variance of the average energy level – p =0,999.

5. Conclusions

Model of the AE resulting signal which was formed at friction of the CM surface layers in frictional contact was conducted. The simulation results, according to the developed model showed that the resulting signal was continuous AE signal with strongly irregular form.

The formed signal can be characterized by the amplitude and energy level and also values of its spread. The simulation results showed that at constant load conditions with increasing tendency of the material to brittle fracture was observed falling of average amplitude and the energy level of AE resulting signal and the values of its spread. From obtained results was defined, that the change of amplitude and energy parameters of AE signals is nonlinear.

The highest increment in the analyzed parameters of AE signals had variance of the average energy level of the AE resulting signal.

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С.Ф. Філоненко[1], О.П. Космач[2]. Вплив поверхонь тертя з композиційних матеріалів на акустичну емісію

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Розглянуто модель результуючого сигналу акустичної емісії, який формується при терті поверхневих шарів фрикційного контакту з композиційного матеріалу. Показано, що формований результуючий сигнал акустичної емісії, який можна характеризувати середнім рівнем амплітуди та енергії, а також величиною їх розкиду, є неперервним сигналом із сильно зрізаною формою. Підтверджено, за постійних умов навантаження пари тертя з композиційного матеріалу зі зростанням схильності матеріалу до крихкого руйнування відбувається падіння середнього рівня амплітуди та енергії результуючих сигналів акустичної емісії, а також величин їх розкиду. За результатами обробки даних моделювання визначено, що зміна амплітудних та енергетичних параметрів формованих сигналів акустичної емісії відбувається нелінійно з зростанням схильності матеріалу до крихкого руйнування. Зазначено, що найбільший приріст аналізованих параметрів сигналів акустичної емісії має дисперсія середнього рівня енергії результуючого сигналу акустичної емісії.

Ключові слова: акустична емісія, амплітуда, дисперсія, енергія, закономірність, композиційний матеріал, рівень, параметр, сигнал, тертя.

С.Ф. Филоненко[1], **А.П. Космач**[2]. **Влияние поверхностей трения из композиционных материалов на акустическую эмиссию**

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Рассмотрена модель результирующего сигнала акустической эмиссии, который формируется при трении поверхностных слоев фрикционного контакта из композиционного материала. Показано, что формируемый результирующий сигнал акустической эмиссии, который можно характеризовать средним уровнем амплитуды и величиной ее разброса, является непрерывным сигналом с сильно изрезанной формой. Установлено, что при постоянных условиях нагружения пари трения из композиционного материала с увеличением склонности материала к хрупкому разрушению происходит падение среднего уровня амплитуды и энергии результирующих сигналов акустической эмиссии, а также величин их разброса. Из результатов обработки данных моделирования определено, что изменение амплитудных и энергетических параметров формируемых сигналов акустической эмиссии происходит нелинейно с увеличением склонности материала к хрупкому разрушению. Отмечено, что наибольшее приращение анализируемых параметров сигналов акустической эмиссии имеет дисперсия среднего уровня энергии результирующего сигнала акустической эмиссии.

Ключевые слова: акустическая эмиссия, амплитуда, дисперсия, закономерность, композиционный материал, параметр, сигнал, трение, уровень, энергия.

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