AVIATION
ISSN 1648-7788 / eISSN 1822-4180
2014 Volume 18(2): 57–63
doi:10.3846/16487788.2014.926640

ACOUSTIC EMISSION IN THE FRICTION OF COMPOSITE MATERIALS

Sergey Filonenko[1], **Aleksandr Kosmach**[2]

[1]National Aviation University, 1 Kosmonavta Komarova Ave., Kiev 03680, Ukraine
[2]Chernigiv State Technological University, Ukraine
E-mails: eduicao@nau.edu.ua; fils01@mail.ru (corresponding author)

Received 27 September 2013; accepted 15 May 2014

Sergey FILONENKO, *Prof., Dr Eng.*
Date and place of birth: 1954, Echmiadzin, Armenia.
Education: Kiev Polytechnic Institute.
Affiliation and functions: Director of the Institute of Information Diagnostic Systems at the National Aviation University since 2008.
Research interests: diagnostics of technological processes, automatic diagnostic systems.
Publications: over 250 scientific papers, 34 patents.

Aleksandr KOSMACH, *PhD Eng.*
Date and place of birth: 1986, Chernigiv, Ukraine.
Education: National Aviation University.
Affiliation and functions: Senior Lecturer at the Department of Mechanical Engineering at Chernigiv State Technological University since 2013.
Research interests: diagnostics of technological processes, signal processing.
Publications: over 40 scientific papers.

Abstract. The model of acoustic emission signal formation during friction and wearing of surfaces of composite materials was examined. The forms of acoustic emission resultant signals were shown. The regularities of parameter change in acoustic emission resultant signals with an increasing rotation speed were determined according to the results of modeling. It was found that theoretical and experimental results of acoustic emission signals registered during friction of composite material surface layers agree well.

Keywords: acoustic emission, friction, load, signal, fracture, wear, composite material, fiber bundle model, rotation, surface, parameter, model, stress.

1. Introduction

Composite materials (CM) and CM coatings are widely used in friction units. Studies on such friction units show that the use of CM reduces the friction coefficient and increases the wear resistance of friction contact surfaces (reducing intensity wear and increasing service life) (Takeshi *et al.* 2009; Koutsomichalis *et al.* 2009; Bria *et al.* 2011). For the analysis and control of the CM-based friction units the traditional characteristics will be used (Bonny *et al.* 2007; Hong *et al.* 2011; Reddappa *et al.* 2011): the coefficient of friction, friction torque, friction force, temperature at the friction contact area and other. However, in practice, these features are sensitive to the processes taking place at the stage of catastrophic wear of the surfaces of frictional contact.

In recent decades, the method of acoustic emission (AE) has become widely spread in the research on friction units. The method is applied to the friction units made from traditional materials (Hase *et al.* 2009; Filonenko, Stadnichenko 2010; Fan *et al.* 2010) and the

CM (Polok-Rubiniec *et al.* 2009; Dobrzanski *et al.* 2006; Pakuła 2011). The research results have proved the high sensitivity of the method to the processes of friction and wear of material surface layers. However, the problems arise in the interpretation of the AE information (changing regularity of AE over time). This relates, first of all, to the stage of normal wear and proximity to the stage of catastrophic wear. At the stage of catastrophic wear a sharp increase in the registered AE parameters is always observed. Problems of interpretation of AE information are caused by the significant amounts of AE data, high resolution and sensitivity of the method to deformation and destruction microprocesses within the surface layers of materials. This refers to the friction units which are made of materials with a crystal structure and CM.

It should be noted that AE information interpretation problems also occur due to the complexity of theoretical research on acoustic radiation which occurs during friction and wear of materials' surface layers. The models and simulation of AE during friction and wear of friction unit surfaces made of traditional materials are considered in (Filonenko *et al.* 2008a, 2008b, 2009). The models are based on the formation of acoustic radiation during the destruction of secondary structures of types I and II. An analytical expression that describes the AE resultant signal with the influence of various factors was obtained. The simulation of AE resultant signals allowed determining the regularities of their parameter change depending on various factors: the load of friction unit, speed of rotation, volume of plastic deforming material, surface damage area and others. The regularities of parameter change were observed at the stage of normal wear approaching catastrophic wear and at the stage of catastrophic wear. The simulation results of the AE signals showed a good level of compliance with the experimental results.

The theoretical research of AE during CM destruction under static loading conditions is considered in articles (Filonenko 2011; Filonenko *et al.* 2010, 2012). The models of AE are based on the destruction of CM elements presented in the FBM concept (fiber bundle model) (Turcotte *et al.* 2003; Shcherbakov 2002; Raischel *et al.* 2005), and the kinetic regularities of the destruction process (Malamedov 1970). The analytical expressions of formed AE signals were received during CM destruction under conditions of tension and operation of shear force. This allows obtaining regularities of AE signal parameter changes when modifying influential factors – speed load changes, physical and mechanical characteristics of the CM, the size of its elements, strength dispersion properties and others. The FBM concept, as noted in article (Shcherbakov 2002), can be used as a simple model when considering the CM wear of friction units. In this case, the CM elements can be viewed as projections on the frictional contact surface destructed by the shear force. The research results received in (Filonenko *et al.* 2012) can be used to creating a model of AE resultant signal that forms during CM wear.

The paper discusses a model of AE resultant signal formation during friction wear of CM-based contact surfaces. The simulation of the AE resultant signal affected by a number of factors will be carried out; also the agreement with experimental results will be discussed.

2. Research results

Taking into account the FBM concept and the kinetics of the destruction process, an expression for the formed AE signal at the destruction of the given CM was presented in (Filonenko *et al.* 2012). It was considered that the CM sample consists of N_0 elements of an identical size. They are evenly distributed over the CM volume. It was thought that the matrix does not influence the process of the CM bearing capacity loss. By the apposition of shear to the CM pattern, the bending moment m and stretching effect F appear on its elements. We consider that the destruction of the CM elements in the model happens in a consecutive order. Besides, the external load is redistributed evenly on the remaining elements which are exposed to the same growing axial deformation. It is considered that the elements become destructed according to the "OR" rule when their deformation reaches the definite threshold level, so that destruction happens due to bending or stretching. Stretching and bending can be considered independently or connected by some expression. Under these conditions, we obtained the expression for the AE signal by taking into account the general expression for stress changes in the case of independent uniform [0, 1] distribution:

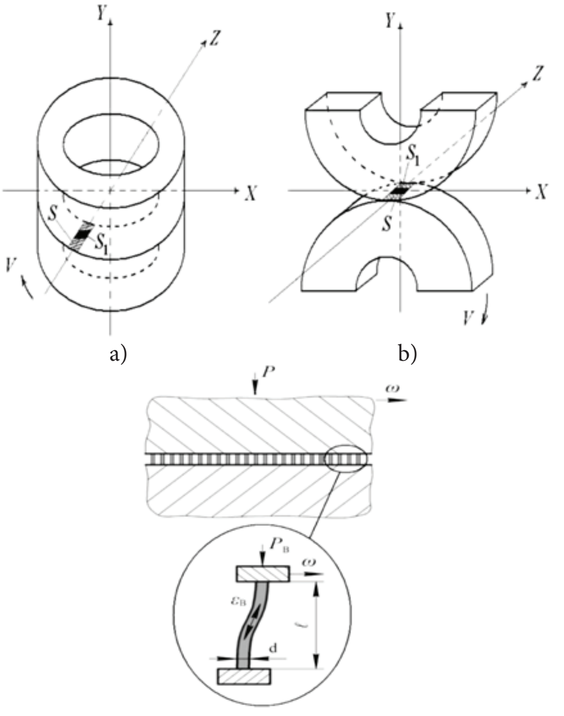
$$
\begin{aligned}
U(t) = {} & U_0 \upsilon_0 [\alpha t(1-\alpha t)(1-g(\alpha t)^{\frac{1}{2}}) - \\
& \alpha t_0 (1-\alpha t_0)(1-g(\alpha t_0)^{\frac{1}{2}})] \text{x} \\
& \text{x}\, e^{r[\alpha t(1-\alpha t)(1-g\sqrt{\alpha t})-\alpha t_0(1-\alpha t_0)(1-g\sqrt{\alpha t_0})]} \text{x} \\
& \text{x}\, e^{-\upsilon_0 \int_{t_0}^{t} e^{r[\alpha t(1-\alpha t)(1-g\sqrt{\alpha t})-\alpha t_0(1-\alpha t_0)(1-g\sqrt{\alpha t_0})]} dt}
\end{aligned}
\qquad (1)
$$

where N_0 indicates the initial quantity of CM elements; υ_0, r – the constants depending on their physical and mechanical characteristics; α – the speed of element loading; t, t_0 – respectively, the current time and the start time of element destruction; g – the coefficient which depends on the geometrical sizes of elements (the area of cross-section and length); $U_0 = N_0 \beta \delta_S$ – the maximum possible displacement at instant destruction of elements; β – the proportionality factor; δ_S – the parameter, the numerical value of which is defined by a form of a single disturbance impulse at the destruction of one element (has the dimension of time).

Expression (1) describes the AE signal formed during the destruction of the given CM.

It is assumed that friction units with CM in the form of rings or rollers are used (Fig. 1a, b). The surface layers undergoing frictional contact in the friction unit are limited to area *S*. The area of contact represents a line of small width. It is assumed that the interface surfaces in the square of *S* consist of ledges which represent CM elements (Fig. 1c). When considering the CM destruction elements in the area *S*, the same initial conditions as in article (Filonenko *et al.* 2012) are accepted: the quantity of elements in conjugation is N_0; the elements are uniformly distributed over the interface surfaces, and the elements have identical physical and mechanical characteristics. It is considered that the matrix does not influence the process of CM element destruction. The contact pressure of mating surfaces (elements) is provided by a perpendicular axial load *P*. The load *P* is constant.

It is assumed that shear load ω was applied to the friction unit. We will accept the conditions of CM element destruction in area *S* provided in article (Filonenko *et al.* 2012)**.** The destruction of elements takes place according to the "OR" rule (deformation of stretching or bending); elements are deformed elastically by destruction; the destruction of the elements happens in a consecutive order; external load is redistributed uniformly on the remaining elements; the threshold levels of destruction are independent and have a uniform [0, 1] distribution. It is assumed that applying shear load ω to CM at a specified value *P*, the destruction of its elements starts at the value of equivalent stress threshold level σ_0.



a)
b)
c)

Fig. 1. A Kinematic scheme of friction units in the form of rings (a) and rollers (b), a scheme of friction contact and an idealized scheme of element destruction in the contact area (c): *V* indicates rotational velocity, *S* – the area of contact interaction; S_1 – the area on the contact surface; *d* – the size of composite material element on the contact surface; *l* – the length of the element; *P*, P_B – indicate, respectively, the contact pressure of surfaces and the element on the contact surface, ω – shear force

Under the indicated conditions, the element destruction in the area of contact interaction *S* will be accompanied by the formation of the AE signal described by expression (1).

It is assumed that the friction unit rotates with constant speed *V*. It provides continuous consecutive change of contact interaction areas S_j, where *j* indicates the number of areas. Then the destruction of each subsequent area S_j will lead to the formation of the AE signal described by expression (1). Under such conditions, the AE resultant signal which can be expressed as the sum of the signals generated by the destruction of each subsequent area S_j will be formed:

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

where *j* indicates a serial number of the *j* contact interaction area (*j* = 0, 1, 2, ..., m); $U_j(t_j)$ indicates the AE pulse signal formed in the *j* contact interaction area described by expression (1), t_j – the time moment of *j* AE signal occurrence.

The time moment of the occurrence of each subsequent AE signal can be expressed as:

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

where Δt_j indicates the time interval between the beginning of the subsequent and preceding AE pulse signal formation.

At a constant speed of contact interaction area variation and the destruction of all elements N_0 in the area *S* (Fig. 1a, b), the time interval Δt_j of AE signal occurrence will be constant. Thus, all AE pulse signals will be identical. If destruction of elements occurs in the variable area S_1 (Fig. 1a, b) of the contact interaction area S, the time interval Δt_j will be variable depending on the location of S_1 and its size (quantity of elements N_0 on area S_1). In this case, the time moment t_j can be expressed as:

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

where δ indicates a random component of the time moment of each subsequent AE signal occurrence. Thus, formed AE pulse signals will differ among themselves, i.e. the parameters of the formed AE signals will vary. It is obvious that the time of AE signal occurrence shown in expression (4) is the closest to real conditions of changing contact interaction areas and the destruction of elements in area *S*.

The modeling of the AE resultant signal is carried out according to (2), taking into account (4) for the following conditions. It is considered that the quantity of the destroyed elements N_0 in each area S_1 (Fig. 1a, b) is constant. Axial load *P* is constant as well, and the destruction of CM elements starts at the threshold stress of destruction σ_0. When the friction unit is rotating, the areas can change their event location in area *S*. Under such circumstances, the staring time of the destruction of each subsequent contact interaction area (the starting time of subsequent AE signal occurrence), according to (4), will be expressed as $t_j = t_0 + j \cdot \Delta t_j + \delta$, where t_0 indicates the starting time of the first contact interaction area destruction, which corresponds to the threshold stress of destruction σ_0.

When modeling, all parameters which enter into expression (1) in the area are considered as relative units. The following values of parameters $\tilde{\upsilon}_0$, $\tilde{r}$, $\tilde{g}$, and $\tilde{\alpha}$ are accepted: $\tilde{\upsilon}_0$ = 100000; $\tilde{r}$ = 10000; $\tilde{g}$ = 0.1 and $\tilde{\alpha}$ = 100. The value Δt_j was equal to $\Delta t_j = 1.6\times10^{-6}$. Value $\tilde{\delta}$ will be changed randomly within the range from 0 to 5×10^{-7}. The starting time $\tilde{t}_0$ of CM destruction and threshold stress of destruction $\tilde{\sigma}_0$ are assumed to be $\tilde{t}_0 = 0.0012$ and $\tilde{\sigma}_0 = 0.101941909$. Values $\tilde{t}_0$ and $\tilde{\sigma}_0$ were defined according to the diagram of equivalent stresses changing over time for the accepted parameter of CM loading speed, according to article (Filonenko 2012).

The results of the AE resultant signal simulation are presented in figure 2 in relative units. Figure illustrates that the AE resultant signal is a continuous signal with a very jagged form. The AE signal is characterized by the average value of the amplitude and the value of its spread.

According to (1), the parameters of the AE pulse signals depend on several factors. Naturally, the change of values of these factors affects the AE resultant signal parameters, according to (2). The modeling of the AE resultant signals in relative units at an increased speed of friction unit rotation is carried out. The same modeling conditions as for the AE resultant signal, shown in figure 2 will be maintained: $\tilde{\upsilon}_0$ = 100000; $\tilde{r}$ = 10000; $\tilde{g}$ = 0.1. Axial load *P* is constant, and the destruction of CM elements begins at a threshold stress of $\tilde{\sigma}_0$ = 0.101941909. The loading speed of the friction unit will change from $\tilde{\alpha}$ = 200 to $\tilde{\alpha}$ = 500. The step increments of $\tilde{\alpha}$ will be $\Delta\tilde{\alpha}$ = 100. Increasing speed $\tilde{\alpha}$ will reduce the starting time of the destruction of each subsequent contact interaction area.

Consequently, the starting time of the occurrence of AE pulse signals will be shortened. In other words, when increasing $\tilde{\alpha}$ for a given value $\tilde{\sigma}_0$, the start time $\tilde{t}_0$ of CM destruction and the time interval between the beginning of subsequent and preceding formation of the AE pulse signal will decrease. Values $\tilde{t}_0$ for each quantity $\tilde{\alpha}$ were determined according to the diagram of equivalent stress variation over time at $\tilde{\sigma}_0$ = 0.101941909, in article (Filonenko *et al.* 2012). Their values were: for $\tilde{\alpha}$ = 200 – $\tilde{t}_0$ = 0.0006; for $\tilde{\alpha}$ = 300 – $\tilde{t}_0$ = 0.0004; for $\tilde{\alpha}$ = 400 – $\tilde{t}_0$ = 0.0003; for $\tilde{\alpha}$ = 500 – $\tilde{t}_0$ = 0.00024. Values Δt_j with increasing $\tilde{\alpha}$ also decreased. Their values were: for $\tilde{\alpha}$ = 200 – $\Delta t_j = 1.1\times10^{-6}$; for $\tilde{\alpha}$ = 300 – $\Delta t_j = 8.0\times10^{-7}$; for $\tilde{\alpha}$ = 400 – $\Delta t_j = 7.0\times10^{-7}$; for $\tilde{\alpha}$ = 500 – $\Delta t_j = 6.0\times10^{-7}$. Value $\tilde{\delta}$ will be changed randomly for $\tilde{\alpha}$ = 200 in the range of values from 0 to 5×10^{-7}. For other $\tilde{\alpha}$ values the quantity $\tilde{\delta}$ is reduced proportionally to the decreased Δt_j.

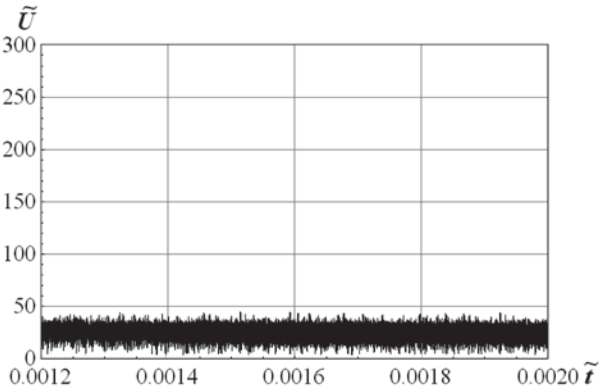


Fig. 2. A diagram of acoustic emission resultant signal amplitude variation over time in relative units during friction of composite material surface layers, according to (2). Simulation parameters: $\tilde{\upsilon}_0 = 10^6$; $\tilde{r}$ = 10000; $\tilde{g}$ = 0.1; $\tilde{\alpha}$ = 100; $\tilde{\sigma}_0$ = 0.10194. Starting time of the destruction $\tilde{t}_0$ = 0.0012; $\Delta\tilde{t}_j = 1.6\times10^{-7}$; $\tilde{\delta}$ indicates changes in the range of values from 0 to 5×10^{-7}

The modeling results of the AE resultant signal in relative units for the accepted conditions are illustrated in figure 3.

Figure 3 illustrates that with increasing $\tilde{\alpha}$ the nature of the AE resultant signals does not change. The AE signals are continuous signals with a very jagged form. They are characterized by an average value of the amplitude and the value of its spread. The results of the average amplitude calculations $\bar{\tilde{U}}$ of the AE resultant signal, its standard deviation $s_{\bar{\tilde{U}}}$ and variance $s^2_{\bar{\tilde{U}}}$ in relative units for each value are shown in table. When $\bar{\tilde{U}}$, $s_{\bar{\tilde{U}}}$ and $s^2_{\bar{\tilde{U}}}$ parameters were determined, the length of the sample was constant and consisted of 5000 values of the calculated amplitudes.

Table. The parameter values of the acoustic emission resultant signals

$\tilde{\alpha}$	$\bar{\tilde{U}}$	$s_{\bar{\tilde{U}}}$	$s^2_{\bar{\tilde{U}}}$
100	28.8	8.4	70.6
200	67.5	19.2	368.6
300	118.2	24.8	615.1
400	162.2	40.1	1608.0
500	207.6	56.3	3169.7

Figure 3 and table show that with increasing $\tilde{\alpha}$ the average level of the AE resultant signal and values of its standard deviation and variance also increase. However, the greatest increase is observed in the average variance of the AE resultant signal amplitude.

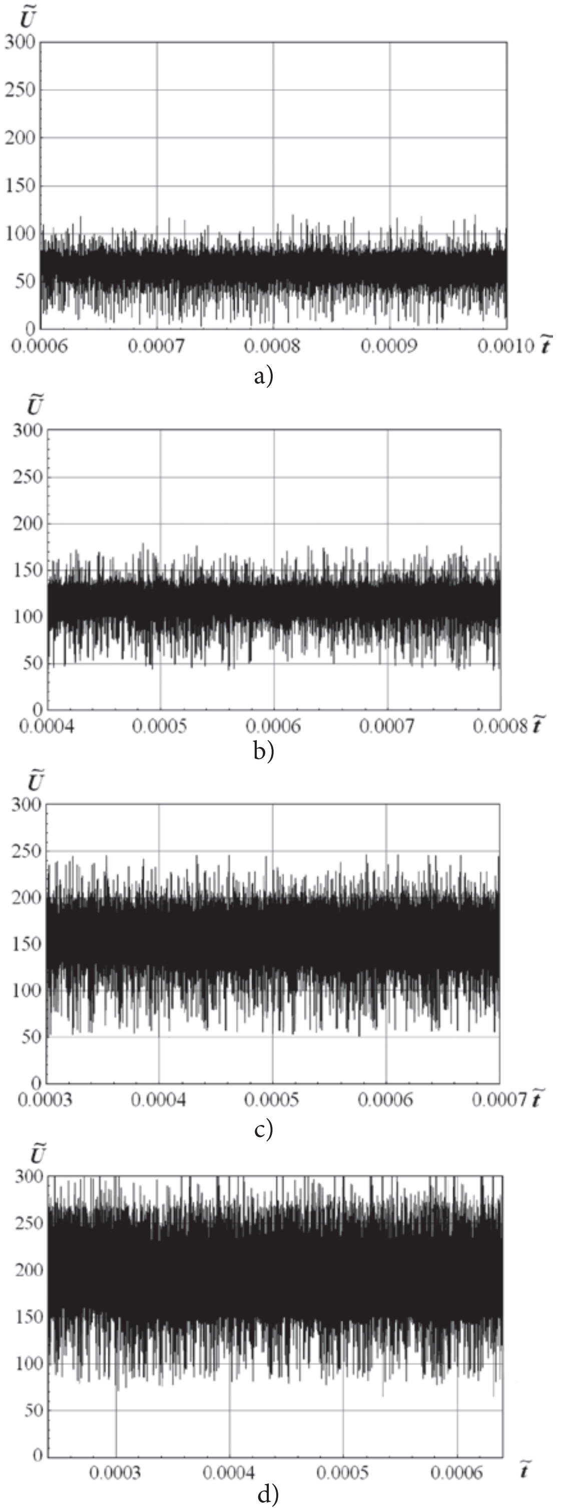


Fig. 3. A diagram of AE resultant signal amplitude variation over time, in relative units during friction of CM surface layers, according to (2). Simulation parameters: $\tilde{\upsilon}_0 = 1000000$; $\tilde{r} = 10000$; $\tilde{g} = 0.1$; $\tilde{\sigma}_0 = 0.101941909$. Values $\tilde{\alpha}$, $\tilde{t}_0$ and $\Delta\tilde{t}_j$ are: a) $\tilde{\alpha} = 200$, $\tilde{t}_0 = 0.0012$, $\Delta\tilde{t}_j = 1.1\times10^{-6}$; b) $\tilde{\alpha} = 300$, $\tilde{t}_0 = 0.0006$, $\Delta\tilde{t}_j = 8.0\times10^{-7}$; c) $\tilde{\alpha} = 400$, $\tilde{t}_0 = 0.0004$, $\Delta\tilde{t}_j = 7.0\times10^{-7}$; d) $\tilde{\alpha} = 500$, $\tilde{t}_0 = 0.00024$, $\Delta\tilde{t}_j = 6.0\times10^{-7}$. The initial value $\tilde{\delta}$ varies randomly in the range from 0 to 5×10^{-7}

Therefore, with $\tilde{\alpha}$ increasing twice (from 100 to 200), values $\tilde{\bar{U}}$, $s_{\tilde{\bar{U}}}$ and $s^2_{\tilde{\bar{U}}}$ increase, respectively, 2.35, 2.30 and 5.22 times. With $\tilde{\alpha}$ increasing 3 times (from 100 to 300), the values $\tilde{\bar{U}}$, $s_{\tilde{\bar{U}}}$ and $s^2_{\tilde{\bar{U}}}$ increase 4.1, 2.95 and 8.71 times respectively. With $\tilde{\alpha}$ increasing 4 times, the values $\tilde{\bar{U}}$, $s_{\tilde{\bar{U}}}$ and $s^2_{\tilde{\bar{U}}}$ increase 5.63, 4.77 and 22.77 times. With $\tilde{\alpha}$ increasing 5 times, the values $\tilde{\bar{U}}$, $s_{\tilde{\bar{U}}}$ and $s^2_{\tilde{\bar{U}}}$ increase 7.20, 6.70 and 45.28 times.

The dependence of the average amplitude changes, its standard deviation and variance are illustrated in figure 4. Figure illustrates that with increasing friction unit rotation speed the increase of the AE resultant signal average amplitude and its standard deviation is almost linear. The increase of the average variance of the AE resultant signal amplitude is not linear.

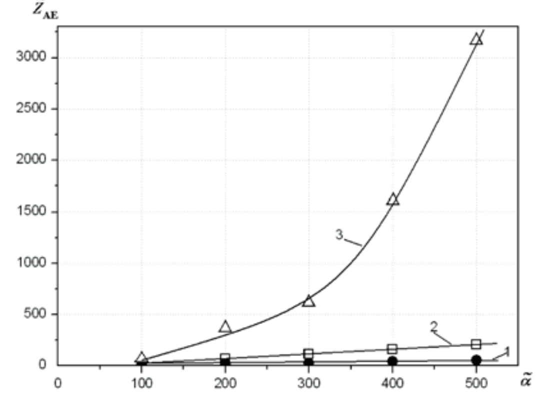


Fig. 4. Dependence of changes in AE resultant signal parameters ($\tilde{Z}_{AE}$) with increasing friction unit rotation speed of CM: 1(●) – average amplitude; 2 (□) – standard deviation of average amplitude; 3 (Δ) – average amplitude variance

The research results showed that during experimental research with increasing friction unit rotation speed, the average level of the AE resultant signal, its standard deviation and variance should increase. The greatest increase is expected in the average variance of the AE resultant signal.

3. Experimental research

Experimental research of AE during CM surface layer friction was conducted on a modernized universal friction machine SMT-1. The operation of the test machine was controlled by a personal computer and specialized software. The software sets and controls the axial load on a friction pair and its rotation speed. The tests measure the friction moment and temperature in the frictional contact zone.

Cylindrical samples of a "bush" type with working front surfaces were used for the tests (Fig. 5). The testing of samples for wear was performed by using the "disk – disk" construction arrangement of interaction. The samples chosen were from aluminum alloy D16 with a CM WC6 coating (hard-alloy coating) and steel 30CMSA. When testing, one of the samples was fixed, and the other sample was mounted on the spindle of the

SMT-1 machine and was rotated at a preset speed. The rotation speed of the tested sample was: 500 rpm and 800 rpm. The axial load on the friction pair was kept constant and was equal to P = 450 N.

The AE signals were registered and processed during friction pair testing. The AE sensor was mounted on the fixed sample. The electrical signal from the AE sensor output enhanced in the amplification path and was recorded by the acoustic-emission complex (AEC) of the mobile computer. The AEC software allows the recording and processing of the AE signal parameters (amplitude, energy, power, average characteristics, etc.), saving signals, drawing conclusions on and analyzing the graphical output relationships with data transmission in Windows mathematical applications.

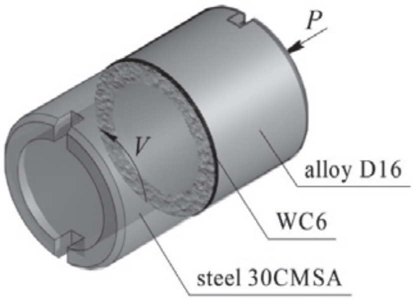


Fig. 5. The interaction scheme of friction unit samples: *P* indicates axial load; *V* – rotation speed

During the experiments, the AE signals were recorded under normal wear. The sampling interval of the input signal (analogue signal to digital code transformation) was equal to 10 microseconds. For further processing of the AE signals average amplitudes were used. The averaging time was 15 milliseconds.

The research results are illustrated in figure 6 as diagrams of average amplitude variation of AE resultant signals during friction of CM surfaces layers. Figure illustrates that the AE resultant signals are continuous signals with a very jagged form. They have an average level of amplitude and value of its spread. In this case, the increasing friction pair rotation speed increases the average level of the amplitude, as well as the value of its standard deviation and variance. The processing of the obtained data showed that when the friction pair rotation speed is at 500 rpm, the average amplitude of the AE resultant signal is $\bar{U}_{500} = 1.72$ V. In this case, the standard deviation $s_{\bar{U}500}$ and variance $s_{\bar{U}800}^2$ of the amplitude are: $s_{\bar{U}500} = 0.1458$ V; $s_{\bar{U}800}^2 = 0.02126\ \text{V}^2$. When the friction pair rotation speed is 800 rpm, the average amplitude of the AE resulting signal is $\bar{U}_{800} = 3.41$ V. The standard deviation $s_{\bar{U}800}$ and variance $s_{\bar{U}800}^2$ of the amplitude are: $s_{\bar{U}800} = 0.2454$ V; $s_{\bar{U}800}^2 = 0.0602\ \text{V}^2$.

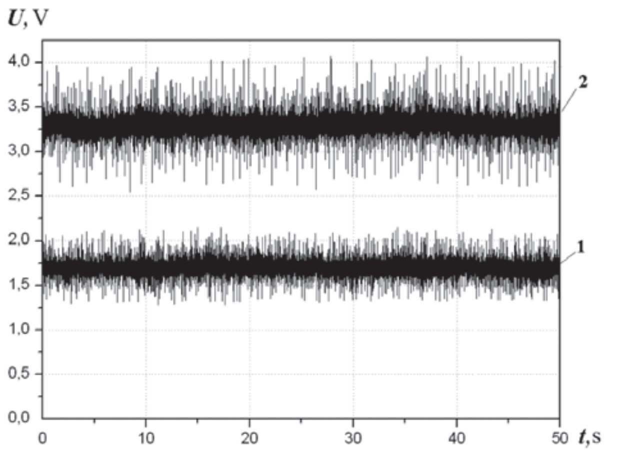


Fig. 6. AE resultant signals recorded during tests of the friction pair with a CM coating wear at different rotation speeds. Rotation speed: 1 – 500 rpm; 2 – 800 rpm. The axial load on the friction pair was 450 N

The results of the calculations show that the increase of the friction pair rotation speed from 500 rpm to 800 rpm (1.6 times) leads to a 1.98 time increase of the AE resultant signal average amplitude. In this case, the standard deviation and variance of the average amplitude increases, respectively, 1.68 and 2.83 times. Apparently, the experimental results agree well with the theoretical ones.

4. Conclusions

The model of acoustic emission signal formation during friction and wearing of composite material surfaces was examined. According to the developed model, the simulation results showed that the AE resultant signal is a continuous signal with a very jagged form. The formed AE signal is characterized by the average value of the amplitude and the value of its spread. The increase in the friction unit rotation speed increases linearly the AE resultant signal average amplitude and its standard deviation. At the same time, the increase in the AE resultant signal average variance amplitude is not linear. The greatest increase in the AE signal parameters is achieved for the AE resultant signal average variance.

The experimental results of the recording and processing of AE resultant signals in CM surface layers during friction of WC6 type agree well with theoretical studies. The recorded AE signals are continuous signals with a very jagged form. The constant axial load value applied to the friction pair increases the average amplitude, the value of its standard deviation and variance due to increasing speed. The greatest increase in the AE resultant signal average variance has also been described.

References

Bonny, K.; De Baets, P.; Van der Biest, O., *et al.* 2007. Edge effects in sliding wear behavior of ZrO2-WC composites and WC-Co cemented, *Materials Science Forum* 561–565: 503–506. http://dx.doi.org/10.4028/www.scientific.net/MSF.561-565.503

Bria, V.; Dima, D.; G. Andrei, G., *et al.* 2011. Tribological and wear properties of multi-layered materials, *Tribology in Industry* 33(3): 104–109.

Dobrzanski, L. A.; Pakuła, D.; Kriz, A., *et al.* 2006. Tribological properties of the PVD and CVD coatings deposited onto the nitride tool ceramics, *Journal of Material Processing Technology* 175: 179–185. http://dx.doi.org/10.1016/j.jmatprotec.2005.04.032

Fan, Y.; Gu, F.; Ball, A. 2010. Modeling acoustic emissions generated by sliding friction, *Wear* 268(5–6): 811–815. http://dx.doi.org/10.1016/j.wear.2009.12.010

Filonenko, S. F. 2011. Influence of non-irregularity the process of composite destruction to acoustic emission signals, *Technological Systems* 1(54): 24–31.

Filonenko, S. F.; Kalita, V.; Kosmach, A. 2012. Destruction of composite material by shear load and formation of acoustic radiatio, *Aviation* 16(1): 5–13. http://dx.doi.org/10.3846/16487788.2012.679831

Filonenko, S. F.; Nimchenko, T. V.; Kosmach, A. P. 2010. Model of acoustic emission signal at the prevailing mechanism of composite material mechanical destruction, *Aviation* 14(4): 95–103. http://dx.doi.org/10.3846/aviation.2010.15

Filonenko, S. F.; Stadnichenko, V. N. 2010. Non-equilibrium self-organization steel – bronze tribosystem on the basis of the acoustic emission method application, *Aviation* 14(3): 71–76. http://dx.doi.org/10.3846/aviation.2010.11

Filonenko, S. F.; Stadnychenko, V. M.; Stahova, A. P. 2008a. Modeling of acoustic emission signals at friction of materials' surface layers, *Aviation* 12(3): 87–94. http://dx.doi.org/10.3846/1648-7788.2008.12.87-94

Filonenko, S. F.; Stadnychenko, V. N.; Stahova, A. P. 2009. Definition of contact stress in friction units on the basis of the acoustic emission method, *Aviation* 13(3): 72–77. http://dx.doi.org/10.3846/1648-7788.2009.13.72-77

Filonenko, S. F.; Stahova, A. P.; Kositskaya, T. N. 2008b. Modeling of the acoustic emission signals for the case of material's surface layers distraction in the process of friction, *Proceedings of the NAU* (2): 24–28.

Hase, A.; Wada, M.; Mishina, H. 2009. Acoustic emission in elementary processes of friction an wear: in-situ observation of friction surface and AT signals, *Journal of Advanced Mechanical Design, Items and Manufacturing* 3(4): 333–344.

Hong, E.; Suh, M.; Kim, Y. S., *et al.* 2011. Tribological properties of copper alloy-based composites reinforced with tungsten carbide particles, *Wear* 270: 591–597. http://dx.doi.org/10.1016/j.wear.2011.01.015

Koutsomichalis, A.; Vaxevanidis, N.; Petropoulos, G., *et al.* 2009. Tribological coatings for aerospace applications and the case of WC-Co plasma spray coatings, *Tribology in Industry* 31(1–2): 37–42.

Malamedov, I. M. 1970. *Principal Physics of Reliability.* L.: Energia. 152 p.

Pakuła, D. 2011. Structure and properties of multicomponent coatings deposited onto salon tool ceramics, *Archives of Materials Science and Engineering* 52(1): 54–60.

Polok-Rubiniec, M.; Dobrzanski, L. A.; Adamiak, M. 2009. Comparison of the PVD coatings, *Archives of Materials Science and Engineering* 38(2): 118–125.

Raischel, F.; Kun, F.; Herrmann, H. J. 2005. Simple beam model for the shear failure of interfaces, *Phys. Rev. E.* 72(4): 11 p.

Reddappa, H. N.; Suresh, K. R.; Niranjan, H. B. 2011. Dry sliding friction and wear behavior of Aluminum/Beryl composites, *International Journal of Applied Engineering. Research, Dindigul* 2(2): 502–511.

Shcherbakov, R. 2002. *On Modeling of Geophysical Problems:* A dissertation for degree of Doctor of Philosophy. Cornell University. 209 p.

Takeshi, T.; Fumiya, T.; Kazuhiro, N., *et al.* 2009. Tribological properties of WC/12Co cermet-Fe-Based metallic glass spray coating, *Transactions of JWRI* 38(1): 75–79.

Turcotte, D. L.; Newman, W. I.; Shcherbakov, R. 2003. Micro and macroscopic models of rock fracture, *Geophes. J. Intern.* 152(3): 718–728.