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CONTROL OF INHOMOGENEOUS MATERIALS STRENGTH BY METHOD OF ACOUSTIC EMISSION

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The ambiguous connection between the results of acoustic emission control and the strength of materials makes acoustic-emission diagnosis ineffective and actualizes the problem of strength and metrological heterogeneity. Inhomogeneity is some deviation from a certain norm. The real object is always heterogeneous, homogeneity is an assumption that simplifies the image of the object and the solution of the tasks associated with it. The need to consider heterogeneity is due to the need to clarify a particular task and is a transition to a more complex level of research. Accounting for heterogeneity requires the definition of its type, criterion and method of evaluation. The type of heterogeneity depends on the problem being solved and should be related to the property that determines the function of the real object, the criterion should be informative, and the way of its evaluation is non-destructive. The complexity of predicting the behavior of heterogeneous materials necessitates the modeling of the destructive process that determines the operability, the formulation of the inhomogeneity criterion, the interpretation of the Kaiser effect, as showing inhomogeneity of the phenomenon of non-reproduction of acoustic emission (AE) activity upon repeated loading of the examined object.

The article gives an example of modeling strength and metrological heterogeneity, analyzes and estimates the informative effect of the Kaiser effect on the danger degree of state of diagnosed object from the positions of the micromechanical model of time dependencies of AE parameters recorded during loading of structural materials and technical objects.

***Key words*:** inhomogeneity of strength condition, strength, destruction, micromechanical model of acoustic emission

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Introduction. Non-destructive testing of strength of structural materials is based on the connection between the results of control and strength characteristics. The heterogeneity of materials and control conditions forms an ambiguous connection, introducing uncertainty in the results of monitoring. The solution of the problem is related to the need to formulate the concepts of heterogeneity and to estimate its quantitative characteristics.

A heterogeneous material is understood as a material with heterogeneous physical properties, a homogeneous material (a material consisting of a number of structural elements), «a certain mathematical model described by means of material functions discontinuous with respect to coordinates (for example, the dependence of the elasticity moduli on coordinates), defining relations (for example, stress-strain relations)» [2-4, 7].

All materials are more or less heterogeneous. Defects of the material and the complexity of the design lead to heterogeneity of their structural, stress-strain and tensile states, the uncertainty of behavior and the need to increase the safety margin, which is not always possible. Indicators of the strength state can be shape, dimensions, coordinates of structural elements, the intensity and scale of the processes of their destruction, deformation or structure transformation, the values of acting or failure stresses, deformations, deformation energies, etc., and the range of these values forms structural, spatial, kinetic, scale, force, deformation or energy criteria of strength inhomogeneity (Fig.1). In particular, the structural criterion of the strength inhomogeneity of a material is related to the parameters of the distribution of the number of defects according to sizes, the scale criterion is related to the hierarchical level of destruction (micro-, meso-, macro-, etc.), the power criterion is the range of values of design stresses, kinetic is connected with a change in the intensity of the processes of material structure transformation. The spatial heterogeneity, manifested in dissipation of destruction, is a prerequisite for the localization of fracture at the moment of reaching a critical concentration of microcracks, which limits the object from complete disintegration into trace elements. The energy heterogeneity of the fracture process is manifested in the spread of the values and the decrease in the average value of the energy of destruction of the structural elements, the kinetic inhomogeneity of the crack

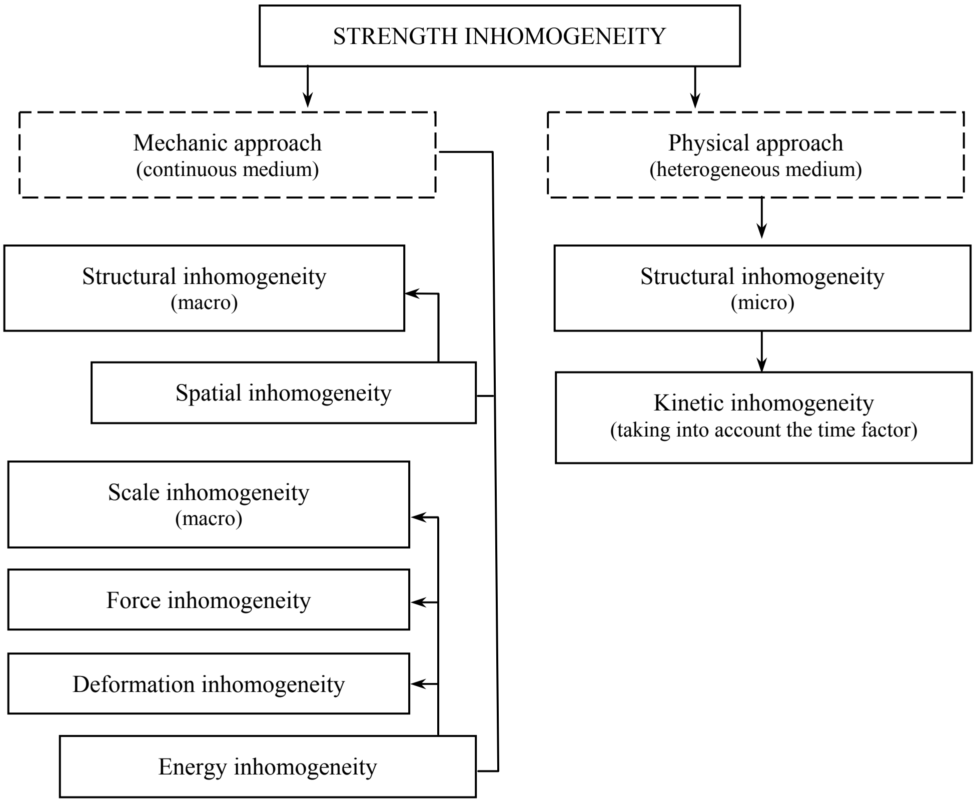

Fig.1. Scheme of material strength inhomogeneity

formation is manifested in the comparative strengthening of the material and the decrease in the intensity of its destruction, the completion point of which is determined by the most durable of the structural elements being destroyed. In cases where heterogeneity is controlled and actively used to optimize the properties of directional control of the structure and composition of the material, the material is called composite.

Various types and degrees of strength heterogeneity in different ways affect the properties of structural materials and the predictability of their behavior. The complexity of predicting the behavior of heterogeneous materials necessitates the modeling of performance-determining processes, the formulation of the criterion for strength inhomogeneity, which should not only be related to the property determining a performance, but also to be prognostic, and the method of its evaluation should not cause excessive damage to the control object, i.e. to be non-destructive. One of the most effective methods for observing the failure process and informative methods of non-destructive control of strength is the method of acoustic emission.

Acoustic emission is the phenomenon of radiation of an object (diagnosis, control, testing) with acoustic waves under the influence of a load or effects of other factors. Acoustic emission (AE) of the material, caused by a change in the structure of the material of the object, is a reflection of the processes that determine the operability of products or structures. Based on the analysis of the AE waves parameters, the acoustic emission method of diagnosing allows finding the coordinates of the defect, assessing the degree of its danger, strength indices, residual resource of the diagnosed object. The task of non-destructive AE-control is informational support of AE-diagnostics, which implies the need to provide correct mechanical effects, metrological conditions for recording AE signals and algorithms for processing its results. The industrial tests carried out under conditions of growing load emphasize the nature of the time dependences of AE parameters during repeated loading or exposure of the load [1, 5, 6, 8, 9]. The absence of signals during a load less than the initial one, as well as the dying out or stabile na-

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ture of the AE, called the Kaiser effect (Fig. 2), are interpreted as a non-hazardous state (section AB, Fig. 2). When AE signals appear long before reaching the value of the initial sample load or accumulate with increasing activity, it is interpreted as a sign of the presence of hazardous defects (section FD, Fig. 2). However, in some cases the accuracy of such a qualitative diagnosis is not high enough, and the manifestation of the Kaiser effect during the acoustic-emission assessment of the state of welded constructions newly introduced into operation and not passed the heat treatment introduces a significant non-definiteness in the diagnosis and requires additional repeated loading, increasing the complexity of control [5].

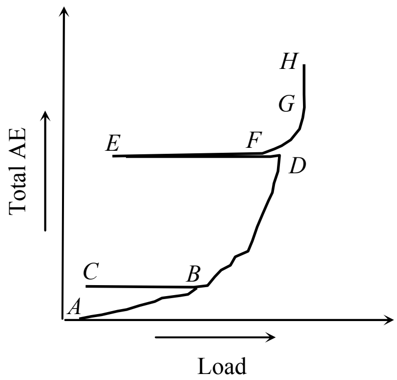

Fig.2. Graphic representation of Kaiser effect

Table 1 examines the relationship between the state of material structure with certain types of strength inhomogeneity, the stages of destruction and their acoustic-emission diagnostic features [3-6, 7, 8]. At the moment, there was a need for a deeper understanding of the AE phenomenon, the justified linkage of its parameters with the indices of the strength non-homogeneity of the objects of control and the creation on the basis of this methodical support for the filtration of AE signals, the quantitative determination of informative indicators of the state, the justification of sufficiency of simplified diagnostic loading, which reduces the complexity of control. This article is devoted to the preparation of the methodological base of these optimization activities.

Table 1

Relation of material structure state with types of strength inhomogeneity, stages of destruction and diagnostic AE features of these stages

State of structure	Stages of destruction	Types of strength inhomogeneity			Diagnostic AE features
		Spatial	Kinetic	Energy	
Destructive (weakened)	Delocalized finely divided inhomogeneous	++	++	++	Fall in AE activity and amplitude before the final destruction, DAT variations, Kaiser effect
Without concentrator	The same	+	+	+	Fall in AE activity and amplitude, DAT variations, Kaiser effect
	Delocalized finely divided homogeneous	+	–	–	DAT variations, ability to evaluate strength indicators
With concentrator	Localized finely divided inhomogeneous	–	+	+	Fall in AE activity and amplitude, DAT variations, Kaiser effect
	Localized finely divided homogeneous	–	–	–	DAT variations, ability to evaluate strength indicators
Development of concentrator	Formation and development of cracks	–	+	+	Signals duration increase, reduction of pauses, increase of overlap factor
	Plastic fracture	–	–	+	DAT variations, ability to evaluate strength indicators, variation of amplitude and length of pauses, Elber effect

Note. «++» – increased inhomogeneity; «+» – essential inhomogeneity; «–» – unessential inhomogeneity; DAT – difference in arrival times of AE to registration channels.

Research methods. To optimize the AE-control and expand the areas of its use, the AE-diagnosis method should be considered as a link in the chain of information collection and processing, which connects the processes occurring in the material with registered AE signals and reliability indicators [21]. In this connection, the description of the destructive process and the

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analysis of experimental data, the formulation of the criterion and the indices of strength inhomogeneity, the development of a method for their quantitative evaluation will be described from the positions of micromechanical models of destruction and time dependences of AE parameters and the use of simulation computer modelling [13 -15]. According to them, the destruction is modeled by the process of accumulation of the concentration of microcracks in a heterogeneous material described by equation

$$C(t) = C_0 \int_{\mu}^{\mu+\Delta\omega} \psi(\omega)\left\{1-\exp\left[-\int_0^t \frac{d\bar{t}}{\theta\ (\omega(\bar{t}))}\right]\right\} d\omega, \tag{1}$$

where t – current time; C_0 – initial concentration of structural elements in the material before destruction; $\theta\ (\omega(t))$ – durability of structural elements, described by Zhurkov's formula [7]:

$$\theta(\omega(t)) = \tau_0 \exp\left(\frac{U_0}{KT} - \omega(t)\right), \tag{2}$$

τ_0 – value of atomic vibrations period order; U_0 – fracture process activation energy; $\omega = \gamma\sigma/KT$ – parameter of strength state; γ – structure-sensitive coefficient; σ – stress; t – current time; K – Boltzmann's constant; T – absolute temperature; $\psi(\omega)$ – function of distribution density of ω value according to structural elements; μ – bottom boundary of ω increment; $\Delta\omega$ – confidence range of ω values distribution according to structural elements.

The introduction of the function $\psi\ (\omega)$ (Fig. 3) makes it possible to describe the failure in the conditions of strength non-homogeneity and introduce its quantitative parameters. Graphically, the distribution can be divided into two parts: a «bell» in which the values of ω are relatively low (they correspond to the most durable structural elements) and vary insignificantly, and the «tail» of the distribution with high values of ω (they correspond to the least durable structural elements), where the variation ω ($\omega 2$) is significant.

The variation of the parameter ω is determined by the variation of two components – the parameter γ (the «technological» component of distribution), which determines the structural inhomogeneity of the material, and the variation of the parameter σ (the «power» component of distribution) is the inhomogeneity of the field of mechanical stresses.

The micromechanical model of time dependences of AE parameters has the following form

$$\xi(t) = V\int_{\Delta t}\int_{f}\int_{U} \Phi(\Delta t, f, U)\,dU df d\Delta t\, C_0 \int_{\mu}^{\mu+\Delta\omega} \psi(\omega)\left\{1-\exp\left[-\int_0^t \frac{d\bar{t}}{\theta_{cp}(\omega(\bar{t}))}\right]\right\} d\omega \tag{3}$$

or

$$\xi(t) = k_{AE}\, C(t), \tag{4}$$

where ξ – primary AE information parameter (number of impulses, total AE, total AE amplitude); k_{AE} – acoustic-emission coefficient (AEC, «audible volume» of material); $\Phi(\Delta t, f, U)$ – density of probability of AE signals by intervals Δt (pauses) between them, amplitude U and frequency f; V – controlled volume.

Computer simulation consists in modelling the concentration of microcracks or the rate microcracks accumulation process on the computer and comparing the simulation

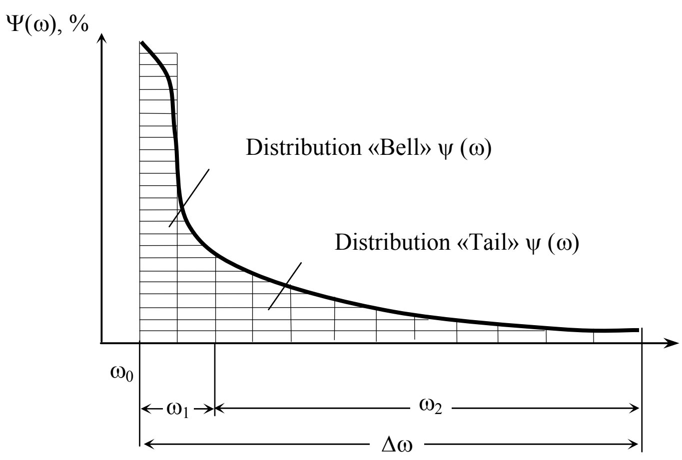

Fig.3. Modelling of material strength inhomogeneity with the help of $\psi(\omega)$ function defining distribution according to structural elements of the material parameter ω of strength state

results with the recorded number of pulses or AE activity for different states of the material and the conditions of its diagnostic loading. The simulation was carried out using the original Destruction Modeling program, written in Delphi 7 environment, under conditions of uniform diagnostic loading with a constant rate of voltage changes. The time dependence of the concentration of microcracks in this case had the following form

$$C(t) = C_0 \int_{\omega_0}^{\omega_0+\Delta\omega} \psi(\overline{\omega})\{1-\exp[-\int_0^t \frac{d\bar{t}}{\Theta(\omega(\bar{t}))}]\}d\overline{\omega} =$$

$$= C_0 \int_{\omega_0}^{\omega_0+\Delta\omega} \psi(\overline{\omega})\{1-\exp[-\frac{1}{\tau_0}\int_0^t \exp(\overline{\omega}\bar{t} - \frac{U_0}{KT})d\bar{t}]\}d\overline{\omega} =$$

$$= \left[\int_0^t \exp[\overline{\omega}\bar{t} - \frac{U_0}{KT}]d\bar{t} = \frac{1}{\overline{\omega}}\exp[\overline{\omega}\bar{t} - \frac{U_0}{KT}]\,|_0^t = \frac{1}{\overline{\omega}}\exp[\frac{U_0}{KT}](\exp[\overline{\omega}t]-1)\right] =$$

$$= C_0 \int_{\omega_0}^{\omega_0+\Delta\omega} \psi(\overline{\omega})\{1-\exp[\frac{1-\exp[\overline{\omega}t]}{\tau_0\overline{\omega}\exp[\frac{U_0}{KT}]}]\}d\overline{\omega}. \quad (5)$$

During the research, we have examined different types of the functions $\psi(\omega)$:

• logarithmic-normal distribution of density function

$$\psi(\omega,\mu,\sigma_3) = \frac{1}{\sqrt{2\pi}\sigma_3\omega}\exp[-\frac{1}{2\sigma_3{}^2}(\ln(\omega)-\mu)^2]; \quad (6)$$

• two-rectangular with weighs 0.99÷0.999 and 0.01÷0.001

$$\psi(\omega,\omega_0,\omega_1,\omega_2) = \begin{cases} 0{,}99/\omega_1, & \omega\in[\omega_0,\omega_0+\omega_1]; \\ 0{,}01/\omega_2, & \omega\in(\omega_0+\omega_1,\omega_0+\omega_1+\omega_2]. \end{cases} \quad (7)$$

The construction of the time dependences of the calculated failure parameters *C* was carried out for various values of the parameters of functions ψ (ω) under different loading regimes. In this case, the *C (t)* models were considered on the interval from zero to the point where the critical concentration $C^* \approx 0{,}01C_0$ was reached, at which the stage of delocalized microcracks formation is completed. When simulating *C (t)*, the following constants were used: $\tau_0 = 10^{-14}$ c, U_0 = 94-120 KJ/mol, K = 8.31 KJ/(Kmol·deg.), *T* = 275 K, C_0 = 10000.

The simulation results were compared with the AE signals recordings results.

The registration was carried out using the automated diagnostic acoustic emission system SDAE-16 (2), described in [3, 4]. The main characteristics of the system: working frequency range 20 ÷ 1000 kHz; The gain of the preamplifier is 34 ± 1 dB, the range of the programmable gain of the main amplifier is from -20 to 40 dB in 0.375 dB steps; programmatically-controlled discrimination threshold; converters with a frequency range of 20-200 kHz were used. Primary measured parameters: time of arrival of the AE signal from the beginning of the test, the rise time of the signal, the duration of the signal, the number of signal emissions, the amplitude of the pulses, and the energy of the pulse. The results of AE registration combined with the invariance of the sample volume and the discrimination thresholds of the AE equipment used talked about the stability of the values of the acoustic emission factor k_{AE}, the correctness (4), and the acceptability of the assumption

$$N_{\tau^*} = k_{AE}C^* = k_{AE}0{,}01C_0 \;\Rightarrow\; k_{AE}C_0 = 100N_{\tau^*}, \quad (8)$$

where N_{τ^*} – the last element of the array, corresponding to total number of AE impulses, registered at the moment of failure of the examined material sample τ^*.

In the course of finding the parameters of the model (3), the optimization problem was solved:

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$$\sum_{t=t_0}^{\tau^*}\left(N_t - k_{AE}C(t)\right)^2 \to \min, \qquad (9)$$

which had the form of

$$\sum_{t=t_0}^{\tau^*}\left(N_t - 100N_{\tau^*}\int_{\omega_0}^{\omega_0+\Delta\omega}\psi(\overline{\omega})\{1-\exp[\frac{1-\exp(\overline{\omega}t)}{\tau_0\overline{\omega}\exp(U_0/KT)}]\}d\overline{\omega}\right)^2 \to \min, \qquad (10)$$

where N_t – elements of data array, corresponding to total number of AE signals, registered at the moment of time *t*.

Discussion of the results. Figure 4 shows the time dependences of the number of pulses of AE-samples of welded joints that have not undergone thermal treatment (Fig. 4, *a*) and amplitude of AE signals of a re-loaded sample (Fig. 4, *b*). It can be seen that the signals appear before reaching the initial load of the samples by 300 s, and their number is very large, although less than at the first loading. It is obvious that the attenuation of AE activity and the irreproducibility of AE parameters with repeated loading of the material are evidence of the irreversibility of the destruction of structural elements and are explained by the inhomogeneity of their strength state, the decrease in the proportion of the most overburdened structural elements in it with low durability in the process of the first loading of the sample parameters ω from the «tail» region of the function ψ (ω). This is a sign of the kinetic inhomogeneity of the cracking process.

The micromechanical model of material destruction breaks the first stage of fine divided fracture into stages of homogeneous and inhomogeneous destruction process. At the non-uniform stage, the least durable elements of the material are subjected to destruction, which are destroyed after the first loading and because of their small amount completely disappear from the process. Homogeneous destruction is less intense, but after the completion of the non-uniform stage begins to dominate. On the time dependence $\ln N_\Sigma$ of re-loadable samples, three sections are distinguished (Fig. 4, *a*):

- kinetic inhomogeneous destruction *a-b*;
- kinetic homogeneous destruction *b-c*;
- destruction after exceeding the previous load *c-d.*

In defective samples, a region of kinetically inhomogeneous destruction is short or absent. The amplitudes of the AE signals after exceeding the initial loading are increased (Fig. 4, *b*). This circumstance is interpreted as a manifestation of the scale effect: the large structural elements are less durable and are

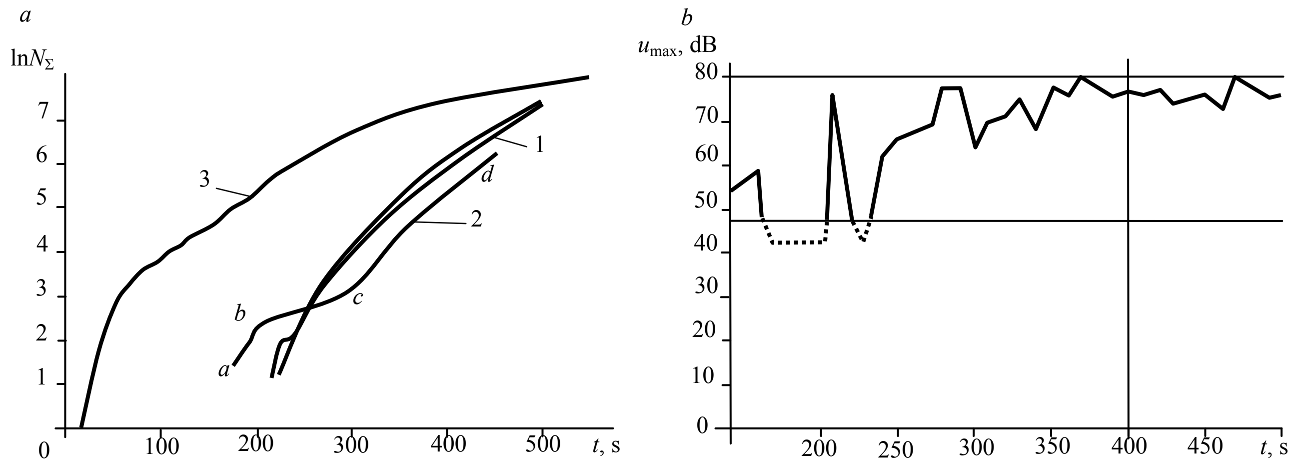

Fig.4. Time dependencies by number of impulses of AE samples of lap-welded joints (*a*) and amplitude of AE signals of re-loaded (A_{rel} = 183 mm^2) sample (*b*):
1 – re-loaded sample with cross-section area of A_{rel} = 183 mm^2; 2 – re-loaded sample, A_{rel} = 525 mm^2;
3 – initially loaded sample, A_{rel} = 301 mm^2

destroyed at the first loading, and the destruction of the remaining smaller elements is accompanied by the release of a smaller amount of energy. Further increase in the amplitude is also associated with an increase in stresses, in which also smaller but stronger structural elements are destroyed. The behavior of the AE parameters of re-loaded samples simulated from these positions under idealized variants of the fracture process is shown in Fig. 5.

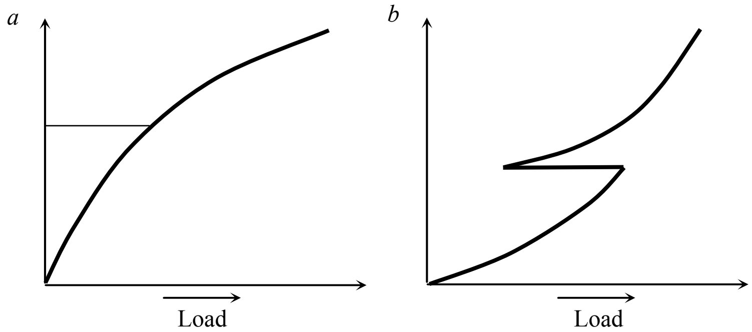

Fig.5. Behaviour of AE parameters during ideal variants of failure process:
a – kinetic inhomogeneous failure process;
b – kinetic homogeneous failure process

The real material is destroyed under conditions of a time-varying strength heterogeneity that changes over time. The degree of heterogeneity bears information about the state of the object: the flow of the process of kinetically inhomogeneous failure indicates a non-hazardous state of the object, and the course of the process of homogeneous destruction, on the contrary, indicates the presence and development of a dangerous defect. This degree can be estimated on the basis of simulation computer modelling, determining the ratio of the parameters of the function ψ (ω). For example, for $\Delta\omega/\omega_0 < 1$ (see Fig. 3), the process of destruction has a homogeneous character, since the length of the «tail» of the function ψ (ω) will be small, and therefore the number of the least durable structural elements is extremely small, otherwise there will be inhomogeneous failure (Fig. 6).

In samples with inhomogeneous structure (with rounded defects) $\Delta\omega/\omega_0 > 1$ 1 (Fig. 7), in samples without distortion of the structure-stressed state (homogeneous failure), $\Delta\omega/\omega_0 < 1$. Samples with increased inhomogeneity and inhomogeneous structure are characterized by the relations $\omega_2/\omega_1 > 10$; $\omega_2/\omega_0 > 10$; $\sigma_3 > 10\mu$ (Fig. 8).

The proposed micromechanical model of AE parameters, in addition to the model of processes associated with strength, includes factors associated with the propagation and recording of the signal, which are unstable (Fig. 9).

Consider the effect of metrological heterogeneity, modeled by the instability of the AEC, on the form of the time dependences of the AE number of pulses $N_\Sigma(t)$. For this we use the physical meaning of AEC as a «audible» volume of material and the graphic meaning of the derivatives.

With the time-dependent value of the AEC, the model of the time dependences of the AE number of impulses, its first and second derivatives takes the form

$$
\begin{gathered}
N_\Sigma(t) = k_{AE}(t)C(t); \\
dN_\Sigma(t)/dt = N_\Sigma(t) = k'_{AE}(t)C(t) + k_{AE}(t)C'(t); \\
d^2N_\Sigma(t)/dt^2 = N''_\Sigma(t) = k''_{AE}(t)C(t) + 2k'_{AE}(t)C'(t) + k_{AE}(t)C''(t).
\end{gathered}
\tag{11}
$$

The absolute values of parameters included into these equations $k_{AE}(t)$, $C(t)$, $k'_{AE}(t)$, $C'(t)$, $k''_{AE}(t)$, $C''(t)$ cannot be defined, but from the point of view of physics, it is clear that $k_{AE}(t) \geq 0$, $C(t) \geq 0$, $C'(t) \geq 0$.

When $N''_\Sigma(t) > 0$ the curve $N_\Sigma(t)$ is bend down, which corresponds to AE activity growth. The growth of activity should be observed for $k''_{AE}(t) > 0$, $k'_{AE}(t) > 0$, $C''(t) > 0$. For stable thresholds of equipment discrimination, the situation $k''_{AE}(t) > 0$ is possible if the average amplitude of the AE signal begins to increase and the form of the amplitude distribution changes in a certain way: the equiprobable distribution goes into exponential, power or distribution with a maximum, which indicates the development of a defect or the growth of a crack. The state of the structure must be recognized as dangerous.

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a *b*

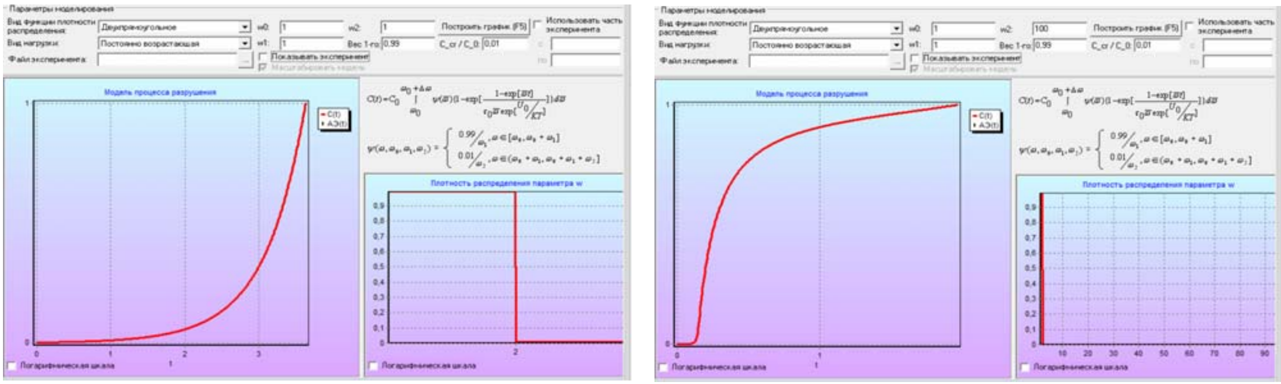

Fig.6. Modelling of homogeneous (*a*) (small «tail» $\psi(\omega)$, $w_2/w_1 = 1$) and inhomogeneous (*b*) (big «tail» $\psi(\omega)$ $w_2/w_1 = 100$) failures with uniform loading of material

a *b*

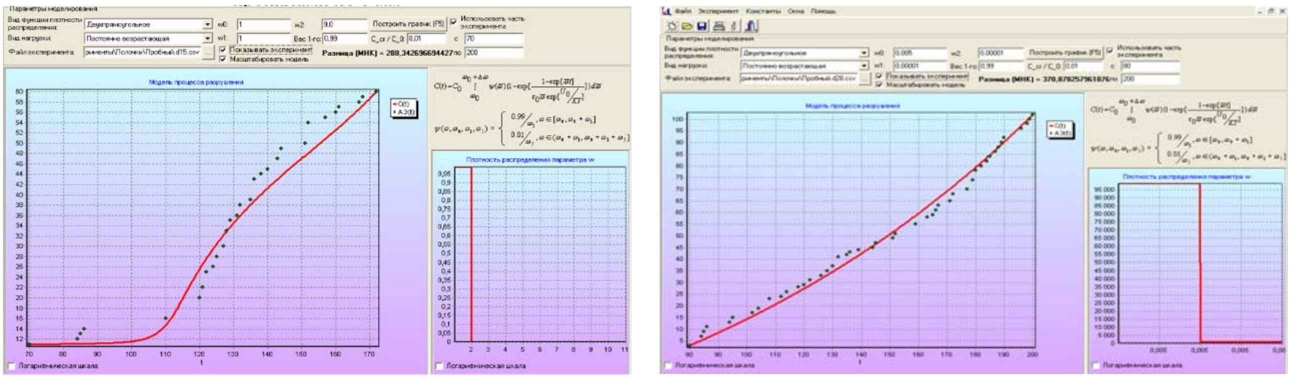

Fig.7. Results of modelling of microcracks formation and registration of AE samples of lap-welded joints:
a – with two rounded side saw cuts at the stage of elastic deformation: two-rectangular distribution $\psi(\omega)$: $\omega_2/\omega_1 > 1$, $\omega_2/\omega_0 > 1$; $\omega_1/\omega_0 = 1$, inhomogeneous failure; *b* – defect-free sample, two-rectangular distribution $\psi(\omega)$: $\omega_1/\omega_0 < 1$, $\omega_2/\omega_0 < 1$, $\omega_2/\omega_1 = 1$, homogeneous failure

a *b*

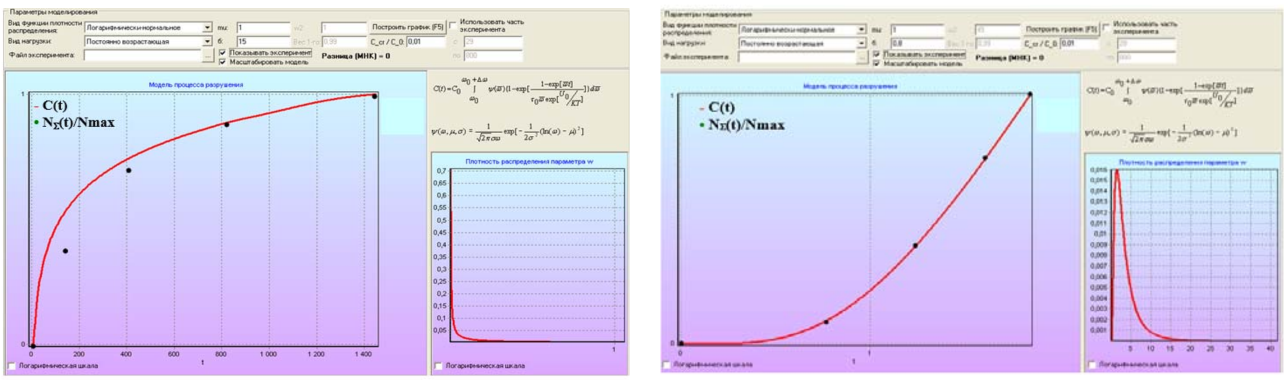

Fig.8. Comparison of registration results for AE sample of cement stone with not-formed highly-inhomogeneous structure (daily age), $\sigma_3/\mu > 1$ (*a*) and structured sample of cement stone (sample age –132 days) $\sigma_3/\mu < 1$ (*b*)

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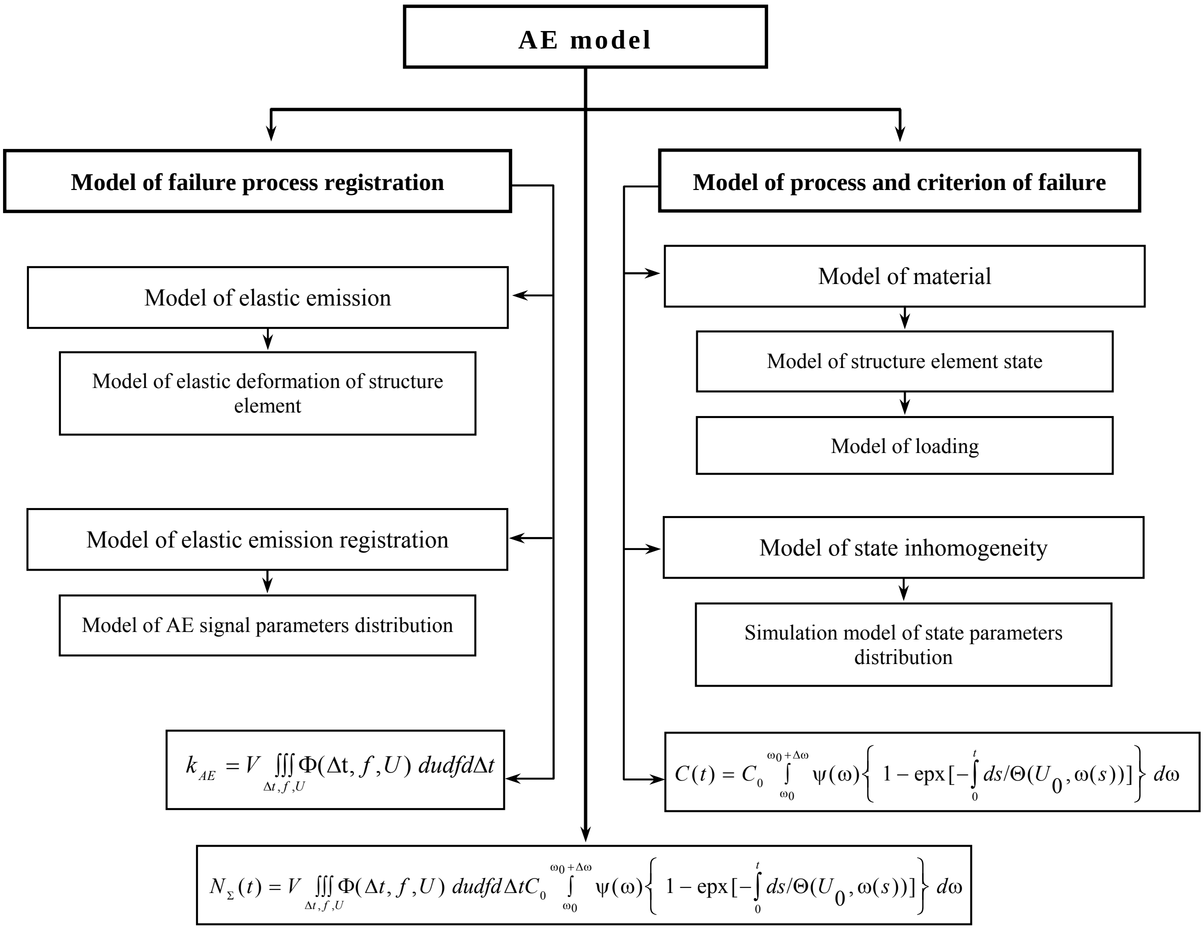

Fig.9. Structure of micromechanical model of AE

The situation $k'_{AE}(t) > 0$ is observed experimentally with the growth of the average amplitude of the AE signals, which occurs when the stresses in the controlled volume of the material increase. Especially great is the value of $k'_{AE}(t)$ for small amplitudes at the beginning of the recording. If the increase in stress occurs due to the growth of the external load and is not related to the growth of the crack, then the increase in the AEC is not a sign of the danger of the state. If $k'_{AE}(t) > 0$ at constant load, this indicates a crack growth, the state of the structure must be recognized as dangerous.

The analysis of the situation with $C''(t) > 0$ is also carried out separately for a constant load and for uniformly distributed loading with a constant velocity. At constant load, when the nominal stresses are constant, the growth of the microcracks concentration C in the material can be either attenuating ($C''(t) < 0$, kinetically inhomogeneous failure) or constant ($C''(t) = 0$, kinetically homogeneous failure), which is observed, as a rule, in the presence of improgressing voltage concentrator.

Thus, the situation $C''(t) > 0$ is possible only with the growth of voltages in the controlled volume, which, when loaded by a constant load, indicates an increase in the crack or progression of the defect, the state of the structure must be taken as emergency. When loaded at a constant speed, the situation $C''(t) > 0$, and hence $N''_\Sigma(t) > 0$, is interpreted not so unambiguously and may indicate:

- progression of the defect with $d^2\ln C(t)/dt^2 > 0$;
- presence of improgressing voltage concentrator with $d^2\ln C(t)/dt^2 \approx 0$;
- kinetic inhomogeneous failure and absence of significant concentration of stress with $d^2\ln C(t)/dt^2 < 0$.

With $N'_\Sigma(t) < 0$ the curve $N_\Sigma(t)$ goes upwards. For this it suffices to satisfy the conditions $k''_{AE}(t) < 0$, $k'_{AE}(t) < 0$, $C''(t) < 0$. The situation $k''_{AE}(t) < 0$ is possible when the average amplitude of the AE signal decreases and the presence of an amplitude distribution of signals that do not contain a maximum, and also with an increase in the mean signal amplitude and a maximum-amplitude distribution.

The growth of the mean signal amplitude contradicts the condition $k'_{AE}(t) < 0$, so we do not consider it. The condition $k'_{\rm AE}(t) < 0$ means a decrease in the proportion of the detected signals due to the output of their amplitudes beyond the recorded range or the signals time overlap. This reduction can be accompanied by either a decrease in the average amplitude of the signal, which is observed with a decrease in the loading rate (controlled by the load indices), or an increase in the average amplitude and an increase in the overlap of signals with increasing loading rate. Since the upper discrimination threshold U^B, as a rule, is quite high, and the growth of the overlap factor contradicts the condition $C''(t) \le 0$, the decrease in AEC will be attributed only to a decrease in the mean signal amplitude. The situation $C''(t) \le 0$, both under constant load and under uniform loading, corresponds to the stage of kinetic inhomogeneous destruction and indicates the absence of a dangerous defect. The state of the structure is not dangerous.

Thus, if the time dependence of the AE number of pulses recorded under exposure to a constant load is in the form of a curve with a convexity downwards ($N''_\Sigma(t) > 0$), then the state of the diagnosed structure should be considered dangerous only on this parameter. Amplitude analysis is not necessary to be conducted in this case. If the time dependence of the AE number of pulses recorded at a constant load or under a uniform loading of the object has the form of a curve with convexity upwards ($N''_\Sigma(t) < 0$), then the state of the diagnosed structure only of this feature should be recognized as not dangerous, the amplitude analysis is also not required. In all other cases of AE control, in which the mean amplitude of the signal and AEC values are varied, the number of pulses recorded and its time dependence are not sufficiently informative, additional analysis of the amplitude distribution is required to diagnose the state. This conclusion is consistent with the ideology of the leading AE-control technologies, and, in particular, with the system of classification of AE sources in the MONPAC technology [5]. Different stages of destruction of the object can be identified (Table 2). To estimate the resource at the stage of homogeneous fracture (following the non-homogeneous one), corresponding to the destruction of structural elements with values of ω from the «bell» region of the function ψ (ω) (see Fig. 3), it is necessary to determine the strength AE indices Y_{AE}, W_{AE}, described in the works [1-4, 7, 10-21].

Table 2

Identification of failure stage and resource evaluation

Stage	Failure stage	Diagnostic indicator of failure stage	Resource evaluation formula (diagnostic T-moment)
I	Delocalized finely divided inhomogeneous	$d^2\xi/dt^2 < 0$ with $\sigma = 0$; $d^2\ln\xi/dt^2 < 0$ with $\sigma = 0$; $dk_{ae}/dt < 0$ ($dP_U/dt < 0$); $\omega_2/\omega_1 > 1$, $\omega_2/\omega_0 > 1$; $\sigma_3 > \mu$; DAT = var	$\tau^* = (1\div10)T$
I	Delocalized finely divided homogeneous	$d^2\xi/dt^2 = 0$ with σ = const; $d^2\ln\xi/dt^2 = 0$ with σ = const; $dk_{ae}/dt = 0$; $\omega_2/\omega_1 < 1$, $\omega_2/\omega_0 < 1$; $\sigma_3 < \mu$; DAT = var	Localization time $\tau^* = f(Y_{AE})$ or $\tau^* = f(W_{AE})$
I	Localized finely divided inhomogeneous	$d^2\xi/dt^2 < 0$ with $\sigma = 0$; $d^2\ln\xi/dt^2 < 0$ with $\sigma = 0$; $dk_{ae}/dt<0$ ($dP_U/dt<0$); $\omega_2/\omega_1>1$, $\omega_2/\omega_0>1$; $\sigma_3 > \mu$; DAT = invar	$\tau^* = (0.1\div0.5)T$
I	Localized finely divided homogeneous	$d^2\xi/dt^2 = 0$ with σ = const; $d^2\ln\xi/dt^2 = 0$ with σ = const; $dk_{ae}/dt = 0$; $\omega_1/\omega_0 < 1$, $\omega_2/\omega_0 < 1$; $\sigma_3 < \mu$; DAT = invar	Time till beginning of concentration growth $\tau^* = f(Y_{AE})$ or $\tau^* = f(W_{AE})$
II	Formation and development of cracks	$d^2\xi/dt^2 > 0$ with σ = const; $d^2\ln\xi/dt^2 > 0$ with σ = const; $dk_{ae}/dt > 0$ ($dP_U/dt < 0$); $\omega_1/\omega_0 > 1$, $\omega_2/\omega_0 > 1$; $\sigma_3 > \mu$; DAT ≈ invar	$\tau^* = (0.01\div0.1)T$
II	Plastic failure	$d^2\xi/dt^2 < 0$ with σ = const; $d^2\ln\xi/dt^2 < 0$ with σ = const; $dk_{ae}/dt < 0$ ($dP_{\Delta t}/dt < 0$); $\omega_1/\omega_0 < 1$, $\omega_2/\omega_0<1$; $\sigma_3 < \mu$; DAT ≈ invar	$\tau^* = (0.01\div0.1)T$

Conclusions. Thus, the application of the micromechanical model of failure process and time dependences of acoustic emission parameters reflecting it, makes it possible to propose an adequate, informative, physically grounded mathematical model of strength and metrological heterogeneity, their quantitative criterion and their evaluation methods, to remove uncertainty in the recognition of the state of controlled heterogeneous objects, to reveal the informativeness of the Kaiser effect and other signs of heterogeneous destruction, making them forecastable.

REFERENCES

1. Kuz'min A.N., Filippov S.Yu. Akustiko Acoustic emission failure detection of lifting equipment. *V mire nerazrushayushchego kontrolya*. 2008. N 2, p. 46-48 (in Russian).

2. Nosov V.V. Assessment of the impact hazard of the rock massif by the results of recording its seismic activity. *Zapiski Gornogo instituta*. 2015. Vol. 216, p. 62-75 (in Russian).

3. Nosov V.V. Diagnostic of machines and equipment. St. Petersburg: Izd-vo «Lan'«, 2016, p. 376 (in Russian).

4. Nosov V.V. Mechanics of composite materials. St. Petersburg: Izd-vo «Lan'«, 2013, p. 240 (in Russian).

5. PB 03-593-03. Rules for the organization and conduct of acoustic emission control of vessels, apparatuses, boilers and process pipelines. Moscow: Gosgortekhnadzor, 2003 (in Russian).

6. Parkhomenko I.V., Yaremenko M.A., Zhbanov Yu.V. et al. Application of the AE method for testing alloy steel under low temperature conditions. *Tekhnicheskaya diagnostika i nerazrushayushchii kontrol'*. 1990. N 1, p. 68-71 (in Russian).

7. Regel' V.R., Slutsker A.K., Tomashevskii E.E. Kinetic nature of solid bodies strength. Moscow: Nauka, 1974, p. 560 (in Russian).

8. Tsarev I.K. Acoustic emission control of bridge crane metal structures. Akusticheskaya emissiya materialov i konstruktsii: Sb. tez. dokl. I Vsesoyuznoi konf. 11-13 sentyabrya 1984 g. Rostov-na-Donu: Izd-vo Rostovskogo un-ta, 1984. Part II, p. 87-88 (in Russian).

9. Shen Gongtian, Wu Zhanwen. Gongtian Shen Study on Spectrum of Acoustic Emission Signals of Bridge Crane. Insight: Non-Destruct. Test. and Cond. Monit. 2010. Vol. 52. N 3, p.144-147.

10. Nosov V.V., Eltchaninov G.S. The Effect of Strength State Nonuniformity on the Acoustic Emission of Structural Materials. *Russian Journal of Nondestructive Testing*. 2011. Vol. 47. N 12, p.824-833

11. Nosov V.V., Kotov Yu.V. Developing Algorithms for Estimating Strength on the Base of Imitating Structural Model of Acoustic Emission.I. Effect of Instability of Acoustic-Emission Coefficient. *Russian Journal of Nondestructive Testing*. 2001. Vol.37. N 9, p.644-649.

12. Nosov V.V., Burakov I.N. A Micromechanical Model of Acoustic Emission of Heterogeneous Materials. *Russian Journal of Nondestructive Testing*. 2004. Vol.40. N 2, p.113-119.

13. Nosov V.V., Burakov I.N. Use of Amplitude Distribution Parametersof Acoustic Emission Signals for Assessing the Strength of Structural Materials. *Russian Journal of Nondestructive Testing*. 2004. Vol.40. N 3, p.157-162.

14. Nosov V.V., Potapov A.I., Burakov I.N. Estimation of the Strength and Lifetime of Technical Objects Using the Acoustic-Emission Method. *Russian Journal of Nondestructive Testing*. 2009. Vol.45. N 2, p.109-117.

15. Nosov V.V. Estimation of the Strength and Lifetime of Welded Constructions Using the Acoustic-Emission Method. *Russian Journal of Nondestructive Testing*. 2009. Vol.45. № 2. P.118-124.

16. Nosov V.V., Lachova E.N. Estimating the Residual Life of Plastically Deformed Welded Joints using Simulation of Their Acoustic Emission. *Russian Journal of Nondestructive Testing*. 2012. Vol.48. N 2, p.75-84.

17. Nosov V.V., Lavrin V.G. Nondestructive Testing of the Quality of Blanks for the Fabrication of Hot-Rolled Strips Using the Acoustic-Emission Method. *Russian Journal of Nondestructive Testing*. 2012. Vol. 48. N 3, p.159-165.

18. Nosov V.V. Automated Evaluation of the Service Lives of Specimens of Structural Materials on the Basis of a Micromechanical Model of the Time Dependences of Acoustic Emission Parameters. *Russian Journal of Nondestructive Testing*. 2014. Vol.50. N 12, p.719-729.

19. Nosov V.V., Potapov A.I. Acoustic Emission Testing of the Strength of Metal Structures under Complex Loading. *Russian Journal of Nondestructive Testing*. 2015. Vol. 51. N 1, p.50-58.

20. Nosov V.V., Matviian I.V. Consideration of Kaiser Effect from the standpoint of strength inhomogeneity and the way of its estimation. In Scientific Reports on Resource Issues: Efficiency and Sustaiability in Mineral Industry – Innovations in Geology, Mining, Processing, Economics, Safety, and Environmental Management. June 2016. Technische University Bergakademie Freiberg, Germany. 2016. Vol.1, p. 147-152.

21. Nosov V.V. On the Principles of Optimizing the Technologies of Acoustic-Emission Strength Control of Industrial Objects. *Russian Journal of Nondestructive Testing*. 2016. Vol. 52. N 7, p. 386-399.

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