Determination of nano characteristics of strength of materials based on the multilevel model of time dependences of acoustic emission parameters

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Abstract. While manufacturing and exploitation of different materials, there could be observed complex physicochemical processes of interaction between their individual components and these components with the environment. Revealing such mechanisms helps to understand their distinct features and optimize technological processes of manufacturing materials with certain characteristics. The solution could be based on interpretation of results of acoustic emission (AE) tests from the perspective of multilevel kinetic model of AE of heterogeneous materials. The article describes the research, the essence of which was to identify systematic changes in the values of the parameters of the AE coefficients included in the model when changing various technological and operational factors on the basis of their operational assessment based on the results of acoustic emission tests.

1. Introduction
Evaluation of the strength properties of materials is traditionally based on the representation of continuum mechanics or simplified kinetic fracture models with acoustic emission [1-7]. However, this approach does not allow us to divide the influence on the strength of natural factors that can be obtained on the basis of a multilevel model of time dependences of acoustic emission parameters. [8-12]. Thus, the purpose of the work is to show how the proposed method allows us to evaluate the strength properties of materials, to investigate the mechanisms of influence of various technological and operational factors on the strength of materials, to optimize production technologies and algorithms for non-destructive testing.

2. Description of method
The basis of the multi-level model is the representation of the material as a heterogeneous medium consisting of separate structural microelements that break down at a certain moment for each element \( \theta \), set by the Zhurkov formula (Fig. 1). The structure has the property of hierarchy, and examples of structural elements can be fibers and matrix elements in composites, grains or their boundaries and non-metallic inclusions in metals and their alloys, amorphous and crystalline regions in polymers, heterogeneity elements in rocks, adhesive and welded joints.

The research methodology consisted in the experimental determination of the influence of various technological and operational factors on the values of the parameters of AE coefficients included in the model. Presented model of timing dependence on a number of AE impulses \( N_C \) has the following view:
\[
N_2(t) = V \iiint_{\Delta t, f, u} \Phi(\Delta t, f, u) u d u d f d t \cdot C_0 \mu^{+\Delta \omega} \psi(\omega) \left\{ 1 - e^{-\int_0^t \frac{d t'}{\theta(U_0, \omega(t))}} \right\} d \omega
\]  

(1)

where \( \theta(U_0, \omega(t)) = \tau_0 e^{[U_0 - \gamma \omega(t)]/(K T)} \) is Zhurkov’s formula.

**Figure 1.** Photos of the structure, a model of a heterogeneous material with structural microelements determining its strength, the formula for their main strength characteristics (a) and the model for converting the fracture parameters of the material into AE parameters (b).

Every parameter of the model (1) has its specific physical nature and depends on distinct factors that allow to reveal mechanisms of the impact of these factors on material’s features:

- parameter \( V = \iiint_{\Delta t, f, u} \Phi(\Delta t, f, u) u d u d f d t \cdot C_0 \) where \( V \) is controlled volume of material (macrolevel), \( \Phi(\Delta t, f, u) \) is AE signals’ density function of pauses’ duration \( \Delta t \), frequency \( f \) and amplitude \( u \), \( C_0 \) is a structural elements’ concentration in material, which characterizes the amount of AE sources which are literally structural elements that can be “heard” via AE equipment during the process of destruction (microlevel);
- parameter \( U_0 \) (activation energy of destruction process of molecular links) doesn’t depend on the state of material structure and is defined through characteristics of interatomic interaction (chemical ties) of a structural element (nanolevel);
- parameter \( \omega = \gamma \omega / KT \) is a parameter, characterizing decrease of an activation energy of a destruction process, and being a strength characteristic of structural microelements (nanolevel);
- parameter \( \gamma \) (activation volume) is a characteristic of a molecular nanostructure of material. Parameters \( \gamma \) and \( \omega \) are faintly sensitive parameter to its chemical nature (nanolevel).
- correspondence of the variables of \( \psi(\omega) \) function characterizes a degree of an inhomogeneity of material’s mechanical state at a molecular level;
The following types of function modern long could be used $\psi(\omega)$:

- logarithmic-normal allocation

$$\psi(\omega, \mu, \sigma_3) = \frac{1}{\sqrt{2\pi\sigma_3}} \exp\left[-\frac{1}{2\sigma_3^2} (\ln(\omega) - \mu)^2\right]$$  \hspace{1cm} (2)

where $\mu, \sigma_3$ are parameters of allocation;

- two-rectangular with scales $0.99 \div 0.999$ and $0.01 \div 0.001$

$$\psi(\omega, \omega_0, \omega_1, \omega_2) = \begin{cases} 0.99/\omega_1, \omega \in [\omega_0, \omega_0 + \omega_1], \\ 0.01/\omega_2, \omega \in [\omega_0 + \omega_1, \omega_0 + \omega_1 + \omega_2] \end{cases}$$ \hspace{1cm} (3)

The point of the survey lay in defining of a systematical variability of the parameters within changes of distinct technological and exploitation factors and was based on the possibility of operational evaluation of these parameters due to the results of acoustic emission tests.

Different samples of heterogeneous materials were exposed to destructive AE tests in the regimen of steady loading with a constant speed of tension’s rise. It was noticed during the tests that the view of timing dependences $N_\Sigma(t)$ was affected by such factors as size of filling material particles, time of isolation of the samples after their manufacturing, heat treatment and chemical saturation of uppermost layers, which can be explained by a change in a degree of structural inhomogeneity of materials.

In the vast majority of an overall number of AE impulses have a view of exponents, aligning in half-logarithmic coordinates (figure 2).

Figure 2. Timing dependences of total number of an AE signals $N_\Sigma$ registered from the start of steady loading of samples of composite materials.

Defining of parameters included in (1) was carried out by solving of the following system:

$$
\begin{cases}
U_0 = \frac{\sigma^d X_{AE} K_T}{\bar{\sigma}} + K_T (35 - \ln X_{AE}) = K_T (\sigma \cdot Y_{AE} + 35 \cdot \ln(\sigma Y_{AE})) \\
\gamma = X_{AE} K_T \bar{\sigma}^{-1} = K_T \cdot Y_{AE} \\
\ln(k_{AE} C_0) = \frac{U_0}{K_T} + \ln N_{\Sigma_0} + \ln(t_0 X_{AE})
\end{cases}
$$ \hspace{1cm} (4)

where $\sigma^d$ is strength limit of a sample, $\bar{\sigma}$ is a speed of tension’s growth in the sample during the time when the sample was steady loaded.

After calculations of the system (2) which were carried out via special software (figures 3-5) graphs and tables were constructed, each point of which corresponded to 6-7 tests. The simulation results were compared with the experimental ones (Figures 5, 6). With close agreement between the theoretical and experimental curves (the value of the “Average approximation error” should be minimal), the desired values of the parameters of the multilevel fracture model were obtained (Figures 3, 4). The research results made it possible to formulate the mechanisms of influence of various technological and operational factors on the strength of materials, reduced mainly to changes in the values of $\gamma$, to optimize production technologies and non-destructive testing algorithms.
Figure 3. Automated function parameter detection. $\psi(\omega) \rightarrow \psi(\gamma)$ of the kinetic model of AE. a - experimental and theoretical curves after approximation, b - distribution of parameter $\gamma$.

Figure 4. Determination of the parameters of kinetic AE model: a) the distribution of the $\gamma$-parameter and $\gamma$ found from the angular coefficient $X_{AE}$ at linear range of dependence; b) determination of the angular coefficient $X_{AE}$ of dependence’s linear range of number of AE impulses’ logarithm in relation to time. For the tested sample: $X_{AE} = 0.017 \text{ s}^{-1}$.

The ratio of the parameters $\omega_0$, $\omega_1$, $\omega_2$, $\sigma$, $\mu$ of the distribution function $\psi(\omega)$ is informative regarding heterogeneity of the stress state of the samples. Samples with inhomogeneous structure and rounded defects have the values $\omega_2/\omega_1$, $\omega_2/\omega_0 > 1$. For the samples made without distortion of the structural-stress state or with “sharp” stress concentrators the ratios were $\omega_2/\omega_0 \leq 1$, $\sigma_2 < \mu$; samples with high heterogeneity and immature structure are characterized by the values $\sigma_2/10 \mu$, $\omega_2/\omega_1 \leq 10$, $\omega_2/\omega_0 \geq 10$ (Figure 5).
Figure 5. Comparison of the results of registration of AE signals from the circular welded sample uniformly compressed with radial load, made without defects with the results’ simulation. The destruction being up to 275 seconds is highly heterogeneous (a,b) \( \sigma_2^{10}\omega_1, \sigma_1^{9}\omega_0, \sigma_3^{10}\mu, \omega_2/\omega_1=14.29, \omega_1/\omega_0=9.3, \sigma_3/\mu=12.

Figure 6. Primary (a) and second (b) loading under 45 kN a welded specimen without holes and with a crack, fracture is homogeneous (\( \mu>\sigma_3 \)), the Kaiser effect is not manifested.

3. Conclusion
Thus, the proposed technique, based on the interpretation of the results of recording acoustic waves from the perspective of a multi-level model of the time dependences of AE parameters, allows one to
evaluate the strength properties of materials, investigate the mechanisms of the influence of various technological and operational factors on the strength of materials, and optimize production technologies and non-destructive testing algorithms.

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