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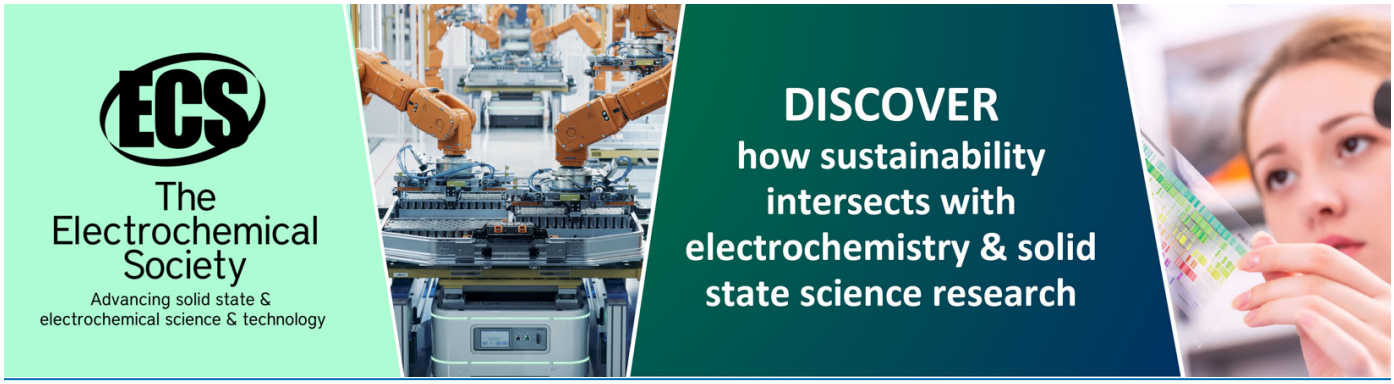

Determination of nanocharacteristics of strength based on acoustic emission diagnostics

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Abstract. During the period of production and exploiting of materials, complex physicochemical processes of interaction of their components with each other and with the environment take place. Identifying the mechanisms of this interaction will help to understand its various aspects and to optimize the technological processes of manufacturing materials with desired properties. The solution of this problem can be based on the interpretation of the results of acoustic emission (AE) tests from the standpoint of a multilevel model of the time dependences of the parameters of AE heterogeneous materials.

1. Introduction

Non-destructive testing of the strength of structural materials is based on the connection of the test results with their strength characteristics. The heterogeneity of the strength properties of different zones of the material makes this relationship ambiguous, introducing uncertainty in the test results. The solution of the problem relates to the necessity of formulating the concepts of heterogeneity and evaluating its quantitative characteristics, that it why in this work we consider the model of the strength heterogeneity of the material and the method for determining its parameters.

Non-uniform material is a material with non-uniform physical properties or heterogeneous material (is a material which consists of many structural elements) or "a certain mathematical model, described using material functions that are discontinuous in coordinates (for example, coordinates of elastic moduli as a function of coordinates) or defining relations (for example, ratios of stresses and strains)"[1-4]. Defects of the material and complexity of the structure lead to heterogeneity of their structural, stress-strain and strength states, behavior uncertainty and the need to increase the safety margin which is not always possible. The most heterogeneous area of a material is its surface, on which various technological damages (scale, various surface defects) accumulate and increased technological and operational stresses occur. Heterogeneity indicators are: differences in the shape, size, coordinates of structural elements, intensities and scales of the processes of their destruction or deformation, values of acting or destructive stresses, deformations, deformation energies, etc., and the scatter of these indicators forms structural, spatial, kinetic, large-scale, force, deformation or energy criteria of heterogeneity (figure 1).

In particular, the structural criterion of material heterogeneity is associated with the parameters of the distribution of the number of defects in size, large-scale - with the spatial level of destruction (nano-, micro-, meso-, macro-, etc.), power - with the variation of the calculated and appropriate stresses, kinetic - with a change in the intensity of material restructuring processes. Spatial

heterogeneity, which manifests itself in the dispersion of the coordinates of acts of destruction, is a prerequisite for the localization of destruction when the critical concentration of microcracks is reached, which limits the object from complete disintegration into microelements. The energy inhomogeneity of the fracture process is manifested in the variation of the ratio of the energy of destruction of structural elements released during fracture and dissipated in the material, the kinetic heterogeneity of the first stage of cracking, the completion of which is determined by the strongest of the destroyed structural elements and decreases in the intensity of its destruction. In cases where heterogeneity is controlled and actively used to optimize properties, directed to the management of the structure, composition and properties of the material, the material is called composite [4].

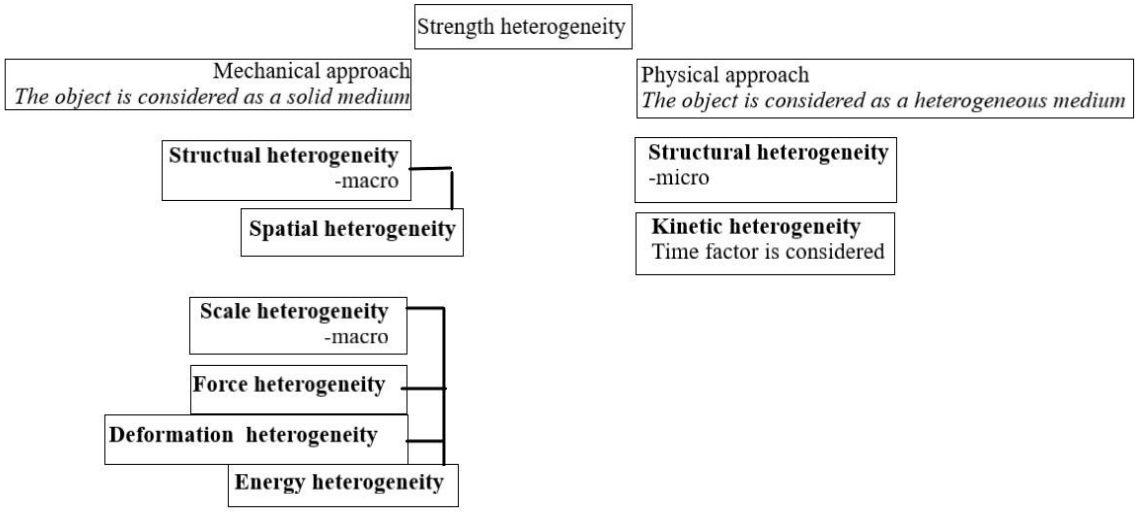


Figure 1. Components of the strength of the heterogeneity of the material.

Different types and degrees of heterogeneity affect the properties of structural materials and the predictability of their behavior in different ways. Energy inhomogeneity is manifested by the spread of pulsed emissions of accumulated energy in the form of acoustic radiation. It is considered [5] that the amplitude of the emitted pulse will depend on the amount of previously stored energy and on its distribution to the formation of a new surface and conversion to acoustic radiation. "In the article [6], this provision was formulated as a new system-forming mechanism for the destruction of a heterogeneous system in the process of fine disintegration based on acoustic emission studies and scanning electron microscopy revealed stages with "sufficient" and "suppressed" dissipative properties. The criticality of a state that limits a resource is determined by the dynamic relationship between the released energy in the discrete act of structural adjustment and dissipative properties of the nearest environment or the system as a whole.

The uncertainty of the behavior of inhomogeneous materials and objects made from them causes the need of the additional diagnostic of effects on the test object. In particular, the production tests carried out under conditions of growing load are substantially inhomogeneous, both new commissioned and welded structures that have served a long period of time, focus on the nature of the time dependences of the AE parameters during reloading [7-11]. The absence of signals under load is less than the original, called the Kaiser effect (figure 2), and the decaying or stable nature of the AE is interpreted as a non-hazardous state (section AB, figure 2), when AE signals appear long before the initial sample load value is reached (Filisiti effect) or accumulate with increasing activity are interpreted as signs of the presence of dangerous defects (FD section, figure 2); AE signals recorded before full discharge (Elber effect) indicate the presence of cracks ins (table 1). However, repeated loading is not always acceptable, and this creates the need to increase the informativeness of the results of registration of AE primary loading signals.

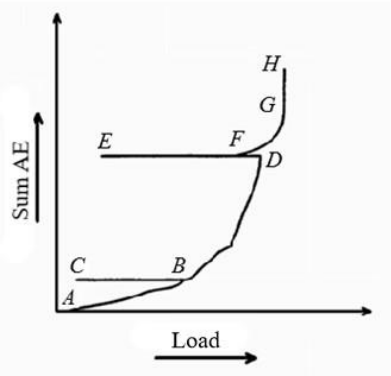


Figure 2. Graphic image of the Kaiser effect observed when testing samples and industrial facilities.

Table 1. The relationship of the state of the structure of the material with the types of strength heterogeneity, stages of destruction and diagnostic AE signs of these stages

Structure state	Stages of destruction	Types of strength heterogeneity			Diagnostic AE signs
		Spatial	Kinetic	Energy	
Destructive (weak)	Delocalized fine inhomogeneous	++[a]	++	++	Fall of AE activity and AE amplitude before final destruction, DRT[d] variation, Kaiser effect
Without hub	Delocalized fine inhomogeneous	+[b]	+	+	Drop of activity, amplitude of AE, variation of DRT[d], Kaiser effect
	Delocalized fine homogeneous	+	–[c]	–	DRT variations, the Felicity effect, the ability to assess the concentration-kinetic strength AE parameters
With hub	Localized fine inhomogeneous	–	+	+	Drop in activity, AE amplitudes, DRT[d] invariant, Kaiser effect
	Localized fine homogeneous	–	–	–	Invariant DRT[d], the Felicity effect, the ability to assess the concentration-kinetic strength AE indicators
Hub Development	Crack formation and growth	–	+	+	Increasing the spread of amplitudes, duration of pauses, the ability to assess the concentration-kinetic strength AE parameters, the Elber effect
	Plastic destruction	–	–	+	Invariant DRT[d], increase overlap ratio

[a] «++» - increased heterogeneity;
[b] «+» - a significant heterogeneity;
[c]«-» - insignificant heterogeneity;
[d] DRT is the difference between the arrival times of AE signals on the registration channels.

Solving the problem is possible on the basis of modeling the processes determining the working capacity and physically grounded formulation of the prognostic criterion for their heterogeneity, developing a non-destructive method for estimating heterogeneity indicators, described in the framework of the information-kinetic approach [3,12]. This article presents the rationale for the relationship of AE parameters with indicators of the strength heterogeneity of the material of test objects, formulated the prerequisites for predicting the resource while eliminating the need for repeated diagnostic loading.

2. Research methods

The most representative characteristic of strength is the time to failure; therefore, the degree of strength heterogeneity of a structural material should be characterized by the spread of rupture times of the structural elements constituting a heterogeneous material, and its evaluation should be made by determining the time dependences of the AE associated with the moment of rupture of the micromechanical model. For the analysis of the adequacy and disclosure of the physical essence of this assessment, its results are compared with the presence in the material of various shapes of defects or the surface area of thermally untreated welds, which is the most defective and overstressed area. The description of the fracture process that determines the strength and the analysis of experimental data, the formulation of the criterion and indicators of strength heterogeneity, the development of a method for their quantitative evaluation is made from the standpoint of the micromechanical fracture model, temporal dependencies of the AE parameters and the use of simulation computer modeling.

The research methodology consisted in the experimental determination of the influence of various technological and operational factors on the values of the coefficients included in the model AE parameters. The proposed model of time dependence (on time t) of the number N_Σ of pulses of AE materials has the following general form:

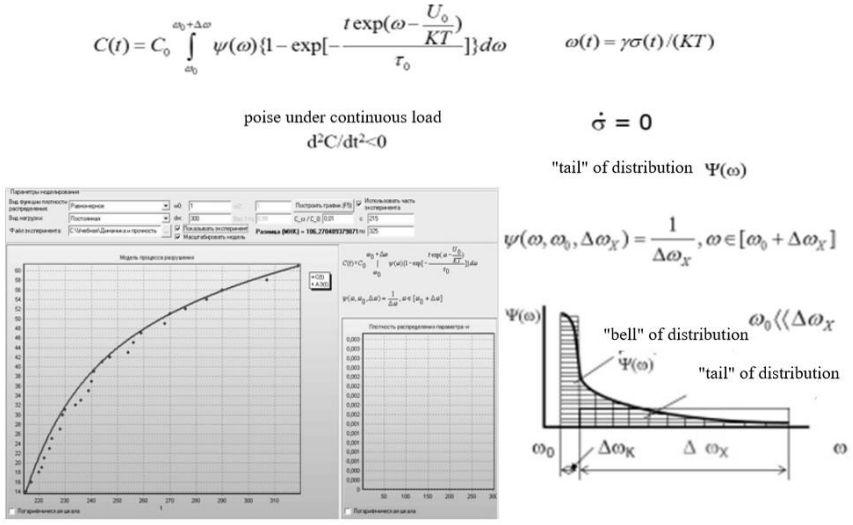
$$N_\Sigma(t)=V\iiint_{\Delta t,f,u}\Phi(\Delta t,f,u)\,du\,df\,d\Delta t\,C_0\int_{\mu}^{\mu+\Delta\omega}\psi(\omega)\left\{1-\exp\left[\frac{-\int_0^t dt'}{\theta(U_0,\omega(t'))}\right]\right\}d\omega \qquad (1)$$

where $\theta(U_0,\omega(t'))=\tau_0\exp\left(\frac{U_0-\gamma\sigma(t')}{KT}\right)$ is Zhurkov's formula.

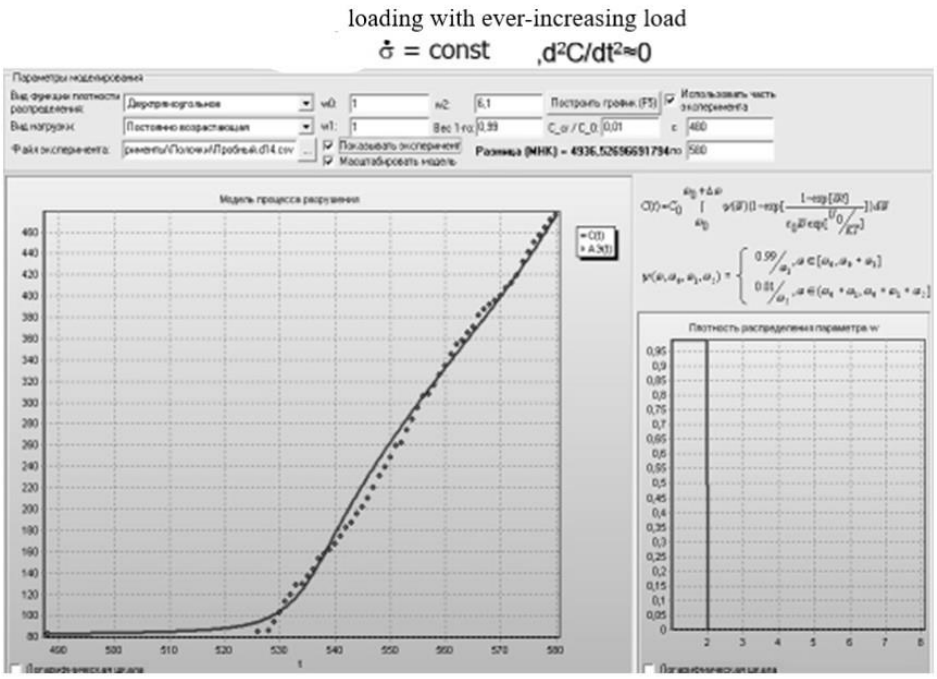
Every parameter of the model (1) has its specific physical nature and depends on distinct factors what allow revealing mechanisms of impact of these factors on material's features:

- Parameter $V\iiint_{\Delta t,f,u}\Phi(\Delta t,f,u)\,du\,df\,d\Delta t\,C_0$ where V is controlled volume of material, $\Phi(\Delta t,f,u)$ is AE signals' density function of pauses' duration Δt, frequency f and amplitude u, C_0 is structural elements concentration in material, characterizes amount of AE sources which are literally structural elements which can be "heard" by AE equipment during the process of destruction;
- parameter U_0 (activation energy of destruction process of molecular links) does not depend on state of material structure and is defined through characteristics of interatomic interaction (chemical ties) of structural element;
- $\omega=\gamma\sigma/KT$ is parameter, characterizing decrease of activation energy of destruction process, and being a strength characteristic of structural microelements;
- parameter γ (activation volume) is characteristic of molecular nanostructure of material. Parameters γ and ω are faintly sensitive parameter to its chemical nature.
- correspondence of the variables of $\psi(\omega)$ function characterizes the degree of heterogeneity of material's mechanical state at a molecular level;

(figure 3) and non-uniform (figure 4) destruction stages.



a)



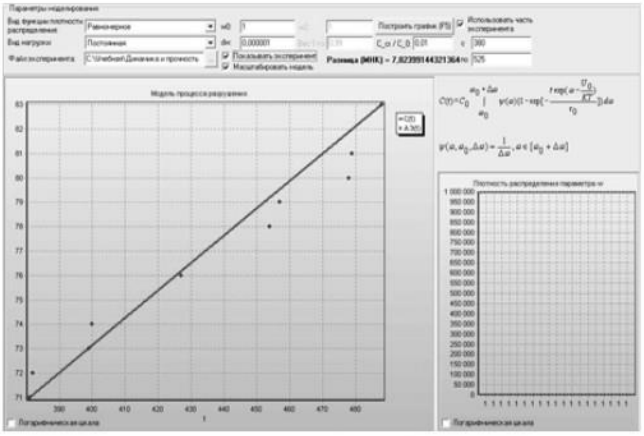
b)

Figure 3. Modeling of the stage of heterogeneous destruction at holding (a) and uniform loading (b) of the material. $\dot{\sigma}$ - average stress growth rate.

poise under continuous load $\dot{\sigma} = 0$

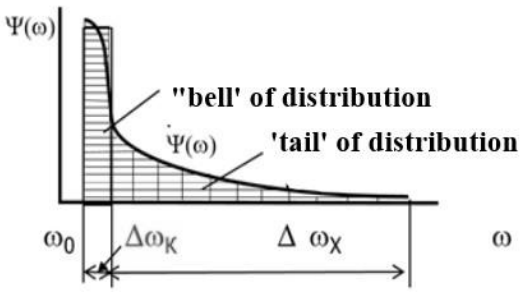
$d^2C/dt^2 \approx 0$

$\omega(t) = \omega = const$



"bell"of distribution $\Psi(\omega)$

$$\psi(\omega, \omega_0, \Delta\omega_K) = \frac{1}{\Delta\omega_K}, \omega \in [\omega_0 + \Delta\omega_K]$$



$N_\Sigma(t,\sigma) = k_{AE}C_o\, t \exp\omega/\{\tau_o \exp[U_o/(KT)]\}$, $N'_\Sigma(t,\sigma) = k_{AE}C_O \exp\omega/\{\tau_O \exp[U_O/(KT)]\}$

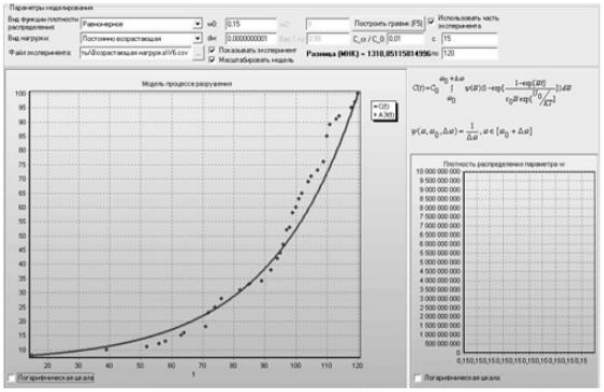
при k_{AE}=const

$d\ln N'_\Sigma/d\sigma = Y_{AE} = d\omega/d\sigma = \gamma/(KT)$

a)

uniform loading with a constant increase in stress

$\dot{\sigma} = const$ $d^2\ln C/dt^2 \approx 0$



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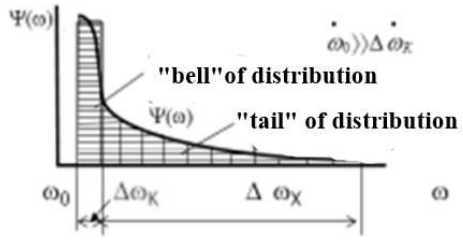


$N_\Sigma(t) = k_{AE}C_O KT\exp[(\gamma\ \dot{\sigma}\ t - U_O)/(KT)]/(\tau_o\ \gamma\ \dot{\sigma})$, $N'_\Sigma(t) = k_{AE}C_O\exp[(\gamma\dot{\sigma}\ t - Uo)/(KT)]/\tau_O$

where k_{AE}=const

$d\ln N_\Sigma/d\sigma = d\ln N'_\Sigma/d\sigma = Y_{AE} = d\omega/d\sigma = \gamma/(KT)$

$d\ln N_\Sigma/dt = X_{AE} = \gamma\ \dot{\sigma}/(KT)$

b)

Figure 4. Simulation of the stage of homogeneous destruction at holding (a) and uniform loading (b) of the material. $\dot{\sigma}$ - average stress growth rate.

There are could be used the following types of function modeling $\Psi(\omega)$:

- logarithmic-normal allocation

$$\Psi(\omega,\mu,\sigma_3)=\frac{1}{(2\pi)^{1/2}\sigma_3\omega}\exp\left[-\frac{1}{(2\sigma_3)^2}(\ln(\omega)-\mu)^2\right],$$

where μ, σ_3 are parameters of allocation;

- two-rectangular with scales 0,99÷0,999 and 0,01÷0,001

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

The estimation of strength inhomogeneity is carried out on the basis of fine-dispersed breaking into the first stage into homogeneous

During a non-uniform stage, the least durable elements of the "loosened" area of material with high dissipative properties are exposed to destruction, which are destroyed after the first loading and, due to their small number, are completely eliminated from the destruction process and no longer manifest themselves upon repeated loading. Homogeneous destruction is less intense, it proceeds in "cramped" conditions in an area with suppressed dissipative properties, however, it begins to dominate with time, without decreasing its intensity when re-loading due to the large number of structural elements of approximately the same strength. Modeled from these positions, the behavior in time of AE parameters re-loaded with an increase in the load of samples (figure 2) is a symbiosis of two idealized variants of the destruction process shown in figure 5.

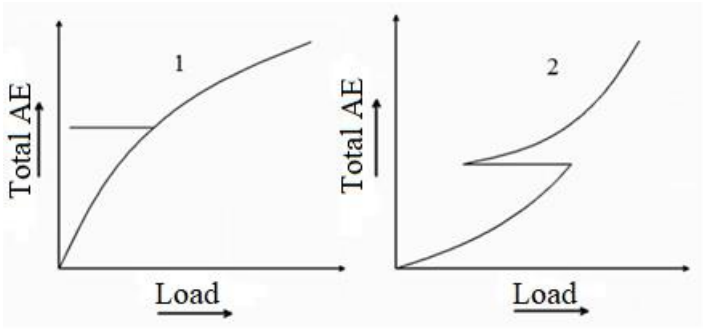


Figure 5. Behavior of AE parameters in idealized variants of the process of destruction:
1 - kinetically inhomogeneous process of destruction, 2 - kinetically homogeneous process of destruction

Thus, the degree of heterogeneity of destruction carries information about the state of the object and its resource. By virtue of the priority of the non-uniform stage, the fact of its registration indicates remoteness before the completion of the first stage and the non-hazardous state of the object, and the course of the stage of uniform destruction, on the contrary, indicates the approach to the end of the first stage and the formation of a macro-crack. It is possible to estimate the degree of approximation by determining the ratio of the parameters of the function (ω). Thus with $\omega_x/\omega_k = \omega_2/\omega_1 \leq 1$, $\omega_2/\omega_0 \leq 1$ (figure 4) the process of destruction has a homogeneous character, since the length of the "tail" of the function ψ (ω) will be relatively small, which means that the number of the least durable structural elements, the destruction of which is intense during the primary and not significant during repeated loading, is extremely small; otherwise, non-uniform destruction of the loosened zone of the material with developed dissipative properties, suggesting the manifestation of the Kaiser effect during repeated loading and the non-hazardous state of the test object [9,10].

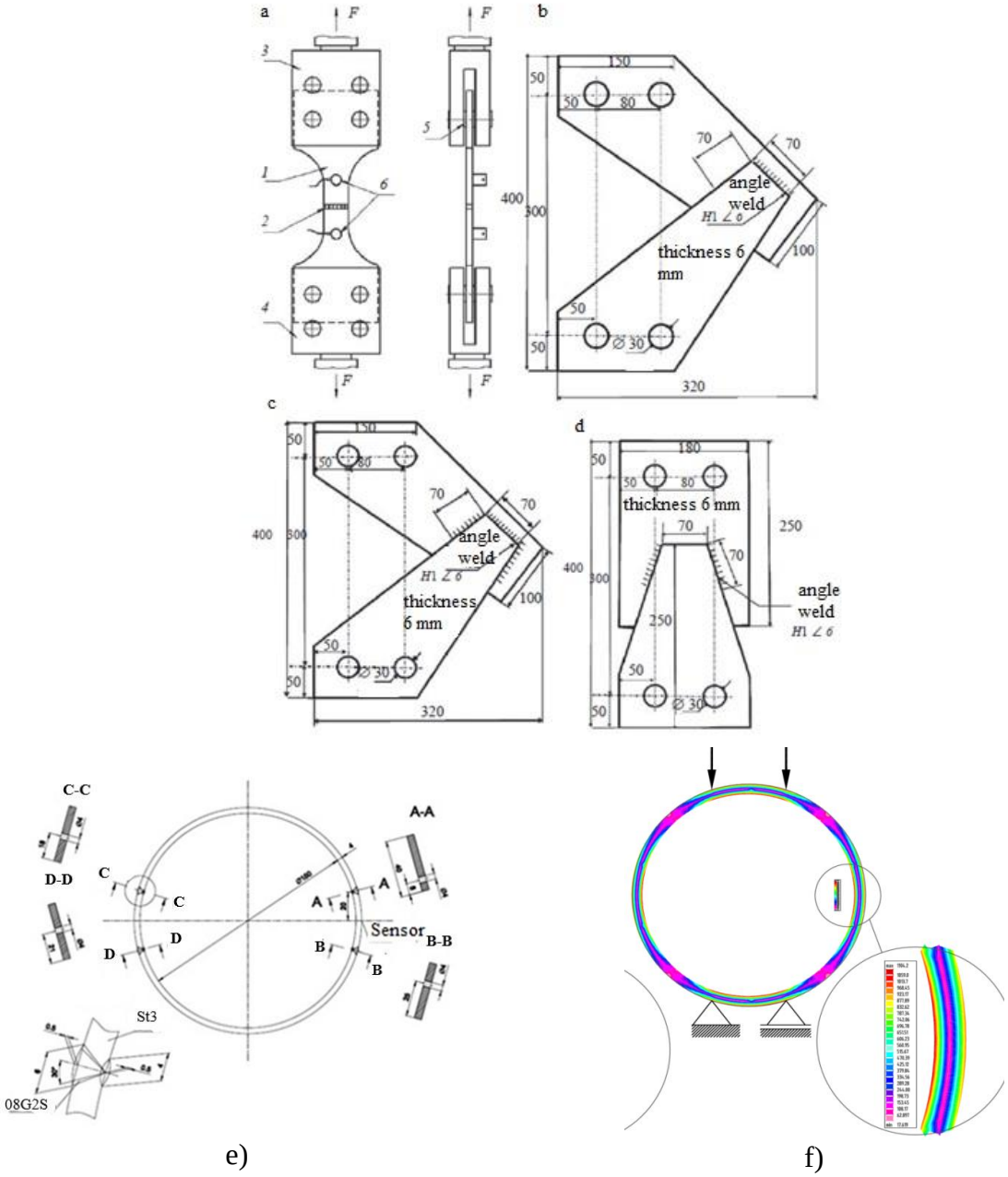
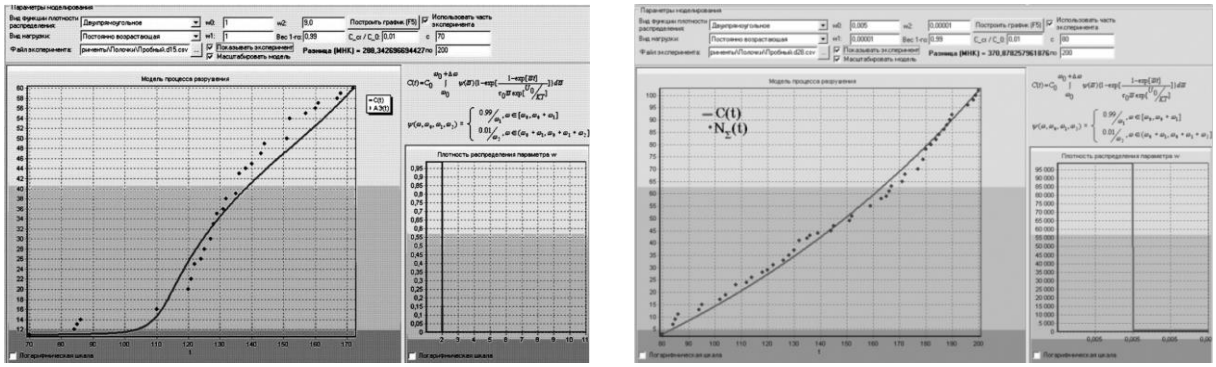
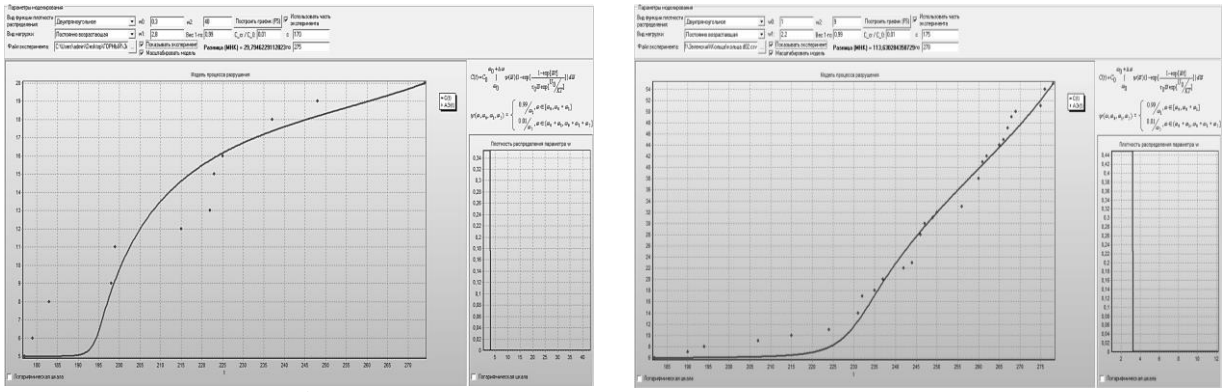


Figure 6. Test pieces with various shapes, types of loading and degree of imperfection: a) butt and b), c), d) -lap-welded joints 1- sample, 2-weld, 3-top grip loading device, 4-bottom grip loading device, 5-finger, 6- TAE; e,f) ring welded samples.



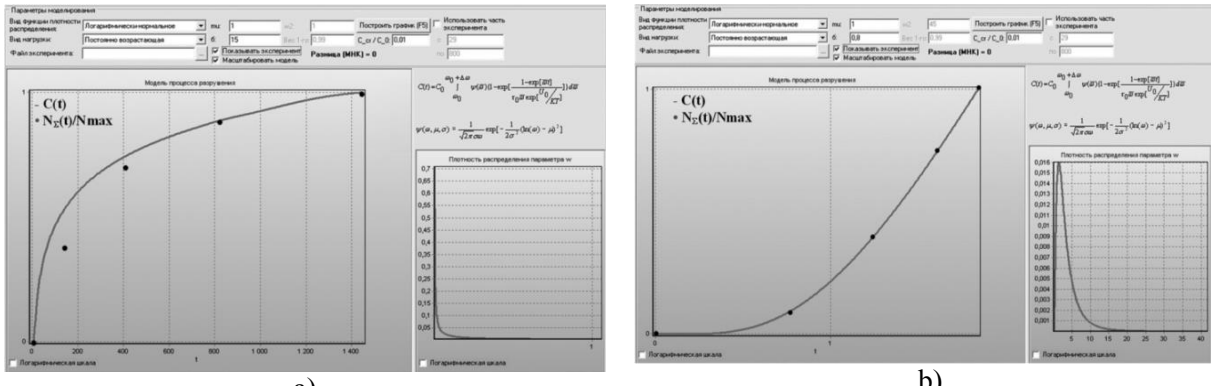
a) b)

Figure 7. Results of simulation of microcrack formation and registration of AE of a butt-welded joint sample: a) -with two rounded side cuts at the stage of elastic deformation, two-rectangular distribution (ω); $\omega_2/\omega_1 > 1$; $\omega_2/\omega_0 > 1$; $\omega_1/\omega_0 = 1$, non-uniform destruction; b) - with two "sharpened" side cuts, two-rectangular distribution ψ (ω), $\omega_1/\omega_0 < 1$, $\omega_2/\omega_0 < 1$, $\omega_2/\omega_1 = 1$, homogeneous failure



a) b)

Figure 8. Results of the simulation microcrack and registration of AE: a) defect-free ring sample: two-rectangular distribution ψ (ω); $\omega_2/\omega_1 > 10$; $\omega_2/\omega_0 > 10$; $\omega_1/\omega_0 > 10$, highly heterogeneous fracture; b) an annular sample with 2 non-through holes made outside: a two-rectangular distribution ψ (ω); $\omega_2/\omega_1 > 1$; $\omega_2/\omega_0 > 1$; $\omega_1/\omega_0 > 1$, non-uniform destruction.



a) b)

Figure 9. Comparison of the results of registration of the AE of a cement stone sample: a) with an unformed highly heterogeneous structure (daily age) $\sigma_3 / \mu > 1$; b) structured sample of cement stone (the age of the sample is 132 days) $\sigma_3 / \mu < 1$.

3. Results and discussion

The results of both their own and third-party research were analyzed. The studies were carried out on welded steel samples (figure 6), registration of AE signals using an automated diagnostic acoustic emission system SDAE-16, described in [3,4]. It was established that for samples with "rounded" defects, the ratio $\omega_x/\omega_k = \omega_2/\omega_1 > 1$, $\sigma_z > \mu$ (σ_z, μ are parameters of the log-normal distribution of the function $\psi(\omega)$, figure. 7a, 8b), that is, heterogeneous failure is observed in samples made with "sharp" stress concentrators $\omega_2/\omega_1 < 1$ (figure.7b, 9b), that is, homogeneous failure is observed. Samples with increased heterogeneity and a structure that was not formed in the process are characterized by the ratios $\omega_2/\omega_1 > 10$, $\sigma_z > 10\mu$ (figure 8a, 9a).

For samples with "acute" defects, the kinetically inhomogeneous fracture section is short or completely absent; upon repeated loading of such samples, the fracture intensity and AE activity does not change (figure 10).

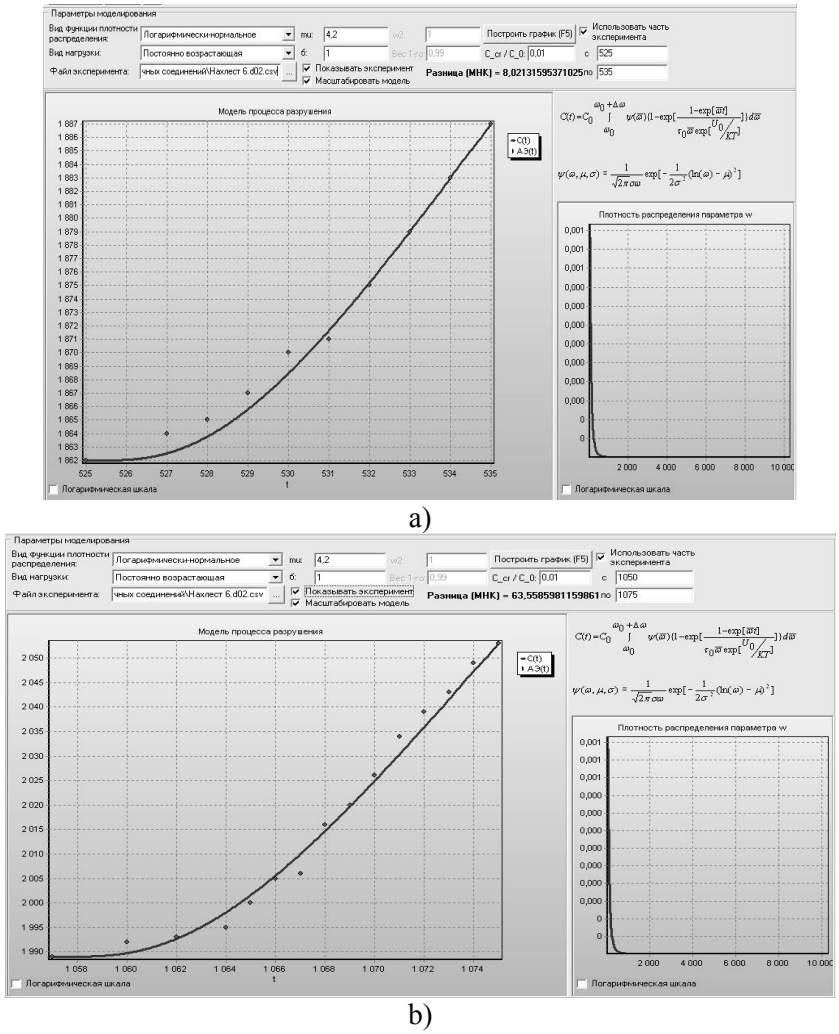


Figure 10. Primary (a) and repeated (b) loading of sample No.6 without holes with a crack with a load of 44-45 kN. Homogeneous destruction ($\mu > \sigma z$).

The physical meaning of the indicated ratios of the parameters of the function $\psi(\omega)$ is also revealed by the comparison with other indices of heterogeneity, and, in particular, according to the results of processing experimental data obtained during AE testing of welded samples of various degrees of surface layer processing, where according to the research work [12] geometrically

heterogeneous elements of heterogeneity. In particular, there was a good correlation of the ratio ω_2/ω_1 with the removed surface area of overlap welds (table 2) and ring welded samples (table 3) [13]. The results of the study indicate a relationship between the parameters of the function parameters (ω) and the area of the most structurally inhomogeneous region of samples of welded joints.

Table 2. Correlation of the ratio of the parameters of the density distribution function ψ (ω) with the area of the removed surface of the samples of overlap welded joints (figure 6b, c, d)

Sample type	Sample number	Defect Type(mm)	Surface removed(mm^2)	ω_2/ω_1
front seam	1	-	0.000	2.833
	2	2 holes Ø6	56.520	3.000
	3	4 holes Ø6	113.040	24.000
	4	1 hole Ø6	28.260	4.667
front seam and 2 flank	5	-	0.000	3.938
	6	6 holes Ø6	169.560	31.429
	7	12 holes Ø6	339.120	242.857
	8	3 holes Ø6	84.780	66.667
	9	3 holes Ø6	84.780	10.667
The correlation coefficient of the ratio ω_2/ω_1 with the area of defects			0.918	

Table 3. Correlation of the ratio of the parameters of the density distribution function ψ (ω) of ring samples (figure 6 d)

Sample number	Defects(mm)	σ_3/μ	ω_2/ω_1	ω_1/ω_0	Area A of the removed surface of the thermally untreated seam, (mm^2)	Maximum stress near defects σ_{max}, (MPa)
5	2 blind holes inside: Ø4 and Ø3	0.92	0.875	0.89	19.6	268
4	2 blind holes outside: Ø2.4 and Ø3.2; flaw 1mm	2.1	4.1	2.2	9.48	247
1	2 through holes Ø4 (burrs)	3.56	6.45	3.1	25	259
3	2 non-through holes: inside Ø3.5 and outside Ø3	3.375	6	2	16.7	266
2	Without defects	12	14.29	9.3	0	188
Correlation coefficient with σ_{max} values		-0.95	-0.89	-0.97		
The correlation coefficient with the values A		-0.75	-0.68	-0.76		

A significant decrease in the strength inhomogeneity is observed under cyclic loading of cast structures. During the primary loading of the first cycle, it is maximum, the number of AE pulses is maximum and decreases with increasing load of the primary loading, while at subsequent loading cycles the correlation between the number of AE pulses and the load increases significantly [14-18].

4. Conclusion

Thus, the proposed criterion of strength inhomogeneity of the material, representing the ratio of the parameters of the micromechanical model of temporal dependencies of acoustic emission parameters and determined by means of simulation computer modeling, is consistent with the criteria of structural and energy heterogeneity, which confirms the adequacy of the criterion. The values of the criterion make it possible to identify various stages of destruction and diagnose the state of the object during the primary loading without the need to use a repeated one, which causes the high diagnostic value of the criterion, making it testable and informative.

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