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MICROMECHANICS, NANOPHYSICS AND NON-DESTRUCTIVE TESTING OF THE STRENGTH OF STRUCTURAL MATERIALS

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Abstract. Non-destructive testing of the strength of structural materials is currently based on the correlation between the results of laboratory tests of the strength of standard macro samples and the strength characteristics of the material in a real object. The heterogeneity of the strength properties of different zones of the material makes this correlation ambiguous, introducing uncertainty in the test results. The solution of the problem relates to the necessity of transition to the micro- and nano- control level that determines the strength, and to the applying of representative micro structural elements of the material and multipurpose physical nanoconstants as reference. The principles of selection of these elements and the method of assessing their strength characteristics are considered. The model proposed in the work has shown its effectiveness both in laboratory samples and in real industrial facilities.
Keywords: acoustic emission, heterogeneous materials, model of acoustic emission

1. Introduction

Non-destructive testing of the strength, forecasting of the resource of structural materials and products made of them is related to the solution of industrial safety ensuring issues and should be based on the development of methods for long-term mechanical prediction of destruction, that allows risk-reducing preventive actions to be made. Special features of damage prediction are assigned to diagnostic methods based on the registration of acoustic emission signals [1,2]. There are two main problems of the application of standard techniques of AE control strength within the solution of the problem of long-term prediction of the residual resource of materials and structures:

1. The low efficiency of the methods of the statistical approach due to the low degree of multipurpose of the used statistical invariants and standards leads to low information content of the applied statistical models. The methods applied on "imperfect" standards do not work well on real objects.
2. The low sustainability of the techniques to interference leads to poor filtering of the recorded signals, instability of correlations, and incorrect setting and solving inverse problems of state recognition.

The development of AE strength control technologies should be limited to:

- comprehensive formulation of the operational aspects of ensuring the efficiency of industrial facilities;
- the allocation of strength as the main criterion of the efficiency of these technologies;
- modelling of determining the strength and residual resource of the damage accumulation process, limited by the moment of achieving the critical damage point;

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- ensuring the possibility of forecasting of that moment based on the correct observation of the damage accumulation process using the AE method.

Reducing of the destabilizing effect of interference, uncertainty in interpretation of signal recording results and the correlation of the criteria of the activity of AE sources with the efficiency criteria of complexly loaded objects is possible based on the principles of informational optimization of AE control.

Currently, AE diagnostics mainly uses a statistical approach to estimation of the state of technical objects. Researchers [3,4] are looking for a correlation between the recorded AE parameters and some external factors (for example, the load). An analysis of the spectrum of an acoustic signal (for example, wavelet analysis [5]) is also widespread. However, a statistical approach to the search for correlation does not provide their stability and protection from destabilizing factors. Creating models of destruction of materials and correlations of AE parameters with this destruction allows one to remove uncertainty in estimation of the state of a technical object.

2. Method

The primary AE information registered during testing is quantitatively described by the micromechanical model of the time dependences of the AE parameters, built on the basis of finely dispersed modelling of the longest first stage of fracture, the pattern of the kinetic theory of strength, and analysis of the results of registration of elastic radiation.

To ensure the information content of the AE control, the values of the primary parameters of the AE should have a meaning of analogues of the material damage and, in particular, be proportional to the concentration $C(t)$ of the resulting micro cracks.

Presented model [6-10] of timing dependence on number of AE impulses N_{Σ} has the following view:

$$N_{\Sigma}(t) = V\iiint_{\Delta t,f,u}\Phi(\Delta t,f,u)dudfd\Delta tC_0\int_{\mu}^{\mu+\Delta\omega}\Psi(\omega)\left\{1-\exp\left[-\int_0^t dt'/\theta(U_0,\omega(t'))\right]\right\}d\omega, \quad (1)$$

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

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

- parameter $V\iiint_{\Delta t,f,u}\Phi(\Delta t,f,u)dudfd\Delta t\, C_0$, where V is controlled volume of material, $\Phi(\Delta t,f,u)$ is AE density function signals of duration pauses 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” via AE equipment during the process of destruction;
- parameter U_0 (activation energy of destruction process of molecular links) doesn’t 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 inhomogeneity of material mechanical state at a molecular level.

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

- logarithmic-normal allocation

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

where μ, σ_3 are parameters of allocation.

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

$$\bullet\,\Psi(\omega,\omega_0,\omega_1,\omega_2)=\begin{cases}\frac{0{,}99}{\omega_1},\ \omega\in[\omega_0,\omega_0+\omega_1];\\ \frac{0{,}01}{\omega_2},\omega\in[\omega_0+\omega_1,\omega_0+\omega_1+\omega_2].\end{cases} \quad (3)$$

- Limited Weibull distribution with the parameters k, λ, and q:

$$\psi(\gamma)=\begin{cases}0,\gamma\epsilon[0,q),\\ A\cdot\left(\frac{k}{\lambda}\right)\cdot\left(\frac{\gamma}{\lambda}\right)^{k-1}\exp\left(\left(-\frac{\gamma}{\lambda}\right)^{k}\right),\gamma\epsilon[q,\infty),\end{cases} \quad (4)$$

where $A=\frac{1}{\int_q^\infty\left(\frac{k}{\lambda}\right)\cdot\left(\frac{\gamma}{\lambda}\right)^{k-1}\exp\left(\left(-\frac{\gamma}{\lambda}\right)^{k}\right)d\gamma}$,

where A – normalization factor; k, λ, q – distribution parameters.

The value of the parameter γ that was obtained of the uniform destruction region was taken as the initial parameter for the start of the iteration procedure of selecting the parameter λ value. The coefficient k value was specified to be equal to 3, which best corresponded to the shapes of the size distributions of actual flaws in weld seams. Model (1) allows to solve the problems of ensuring reliability and supplements traditional approaches [1-5,11].

The point of the survey laid in defining of 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 results of acoustic emission tests.

Different samples of heterogeneous materials were exposed to destructive AE tests in regimen of steady loading with constant speed of tension rise. During the tests it was possible to notice 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, what can be explained by changing of degree of structural inhomogeneity of materials.

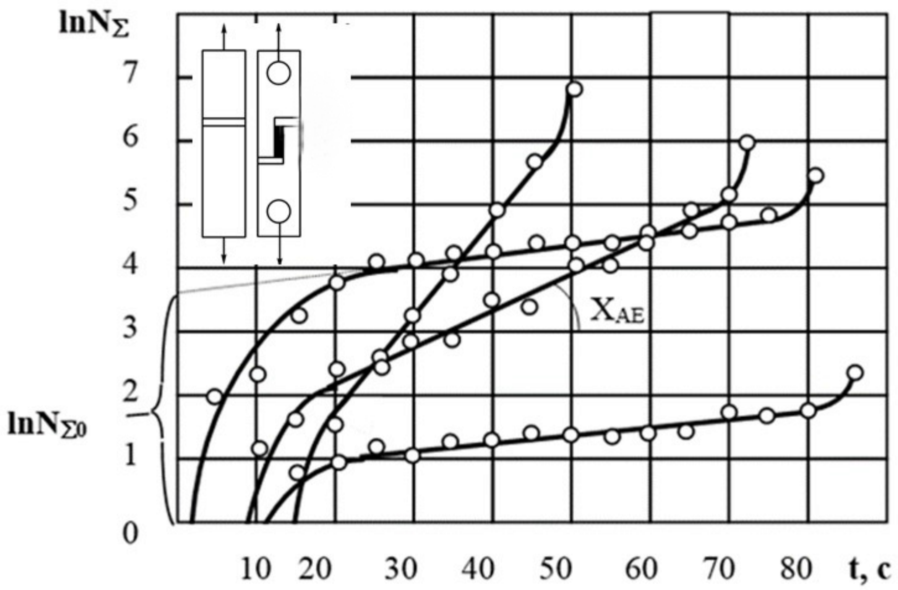

Fig. 1. Timing dependences of total number of AE signals N_Σ registered from the start of steady loading of samples of composite materials

In the vast majority of cases timing dependences of number of AE impulses were considered as exponents, aligning in half-logarithmic coordinates (Fig. 1).

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

$$\begin{cases} U_0 = \sigma_d^* X_{AE} KT/\dot{\sigma} + KT(35 - \ln(X_{AE})) \stackrel{\cdot}{=} KT(\sigma Y_{AE} + 35 - \ln(\dot{\sigma} Y_{AE})) \\ \gamma = X_{AE} KT/\dot{\sigma} = K\dot{T} \cdot Y_{AE} \\ \ln(k_{AE} C_0) = \frac{U_0}{KT} + \ln(N_{\Sigma^0} + \ln(\tau_0 X_{AE})) \end{cases}, \quad (5)$$

where σ_d^* is strength limit of a sample, $\dot{\sigma}$ is speed of tension growth in the sample during the time when the sample is loaded.

After calculations of the system (5) which were carried out via special software (Figs. 2-4) there were constructed tables and charts with every dot corresponding to 6 to 7 tests. Results of the research allowed to formulate mechanisms of impact of distinct technological and exploitation factors on material strength and to optimize manufacture technologies and algorithms of non-destructive control.

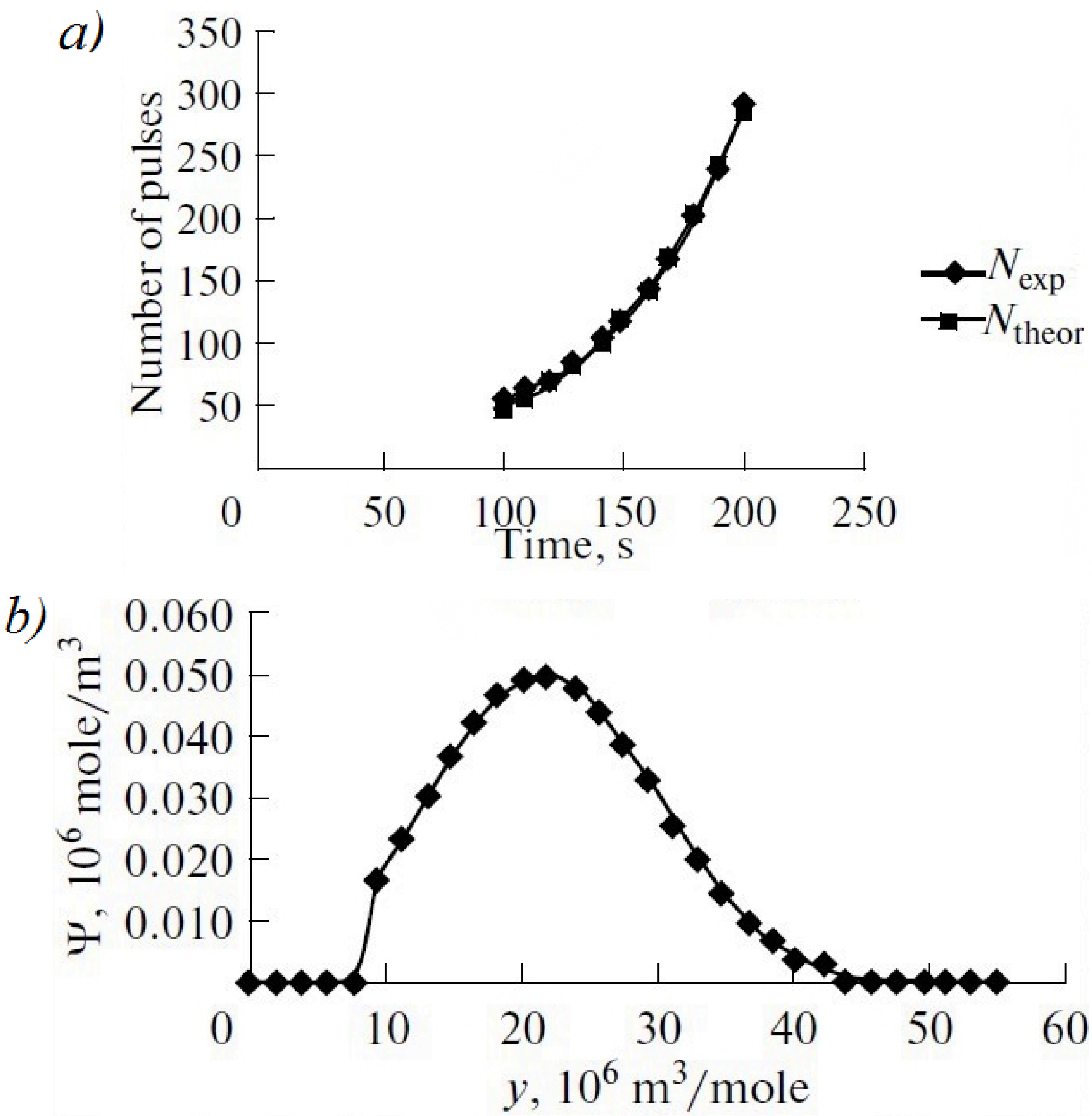

Fig. 2. Automated determination of parameters of function Ψ(ω)→ Ψ(γ) of the kinetic AE model. a – experimental and theoretical curves after approximation, b - the distribution of the γ-parameter

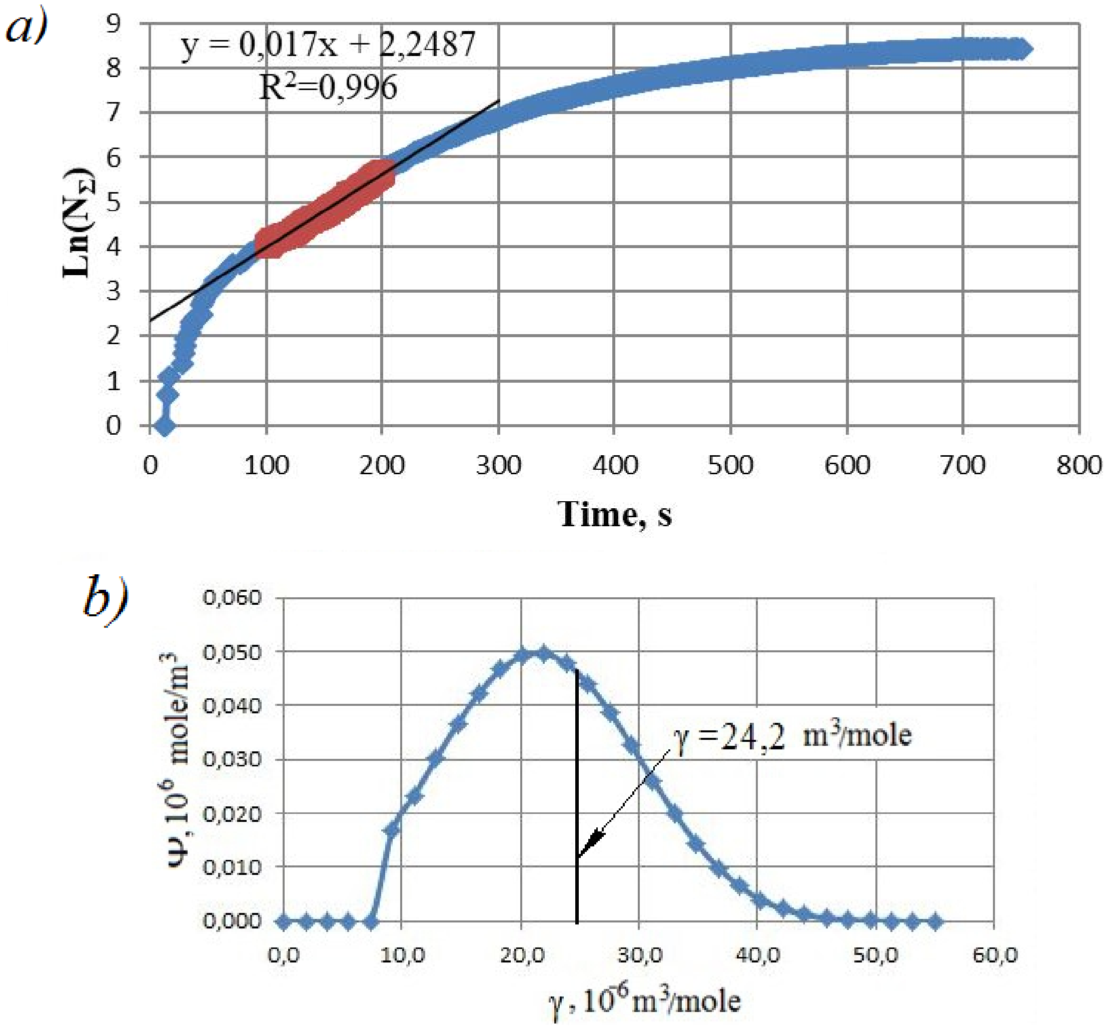

Fig. 3. Determination of parameters of kinetic AE model: a) determination of the angular coefficient X_{AE} of linear dependence range logarithm of number of AE impulses related to time. For the tested sample: X_{AE} = 0,017 s^{-1}; b) the distribution of the γ-parameter and γ found from the angular coefficient X_{AE} at linear range of dependence

The micromechanical destruction model of the material divides the first stage of the finely dispersed destruction of the material into homogeneous and heterogeneous destruction stages that conforms the two-stage separation of dissipative properties. During the heterogeneous stage, the least durable elements of the material are subjected to destruction; these elements are destroyed after the first loading and due to their small quantity are completely eliminated from the process of destruction. Homogeneous destruction is less intense, however, after the termination of the heterogeneous stage begins to dominate.

The connection between the state of the material structure and some types of strength heterogeneity and stages of destruction and their acoustic emission diagnostic signs is considered in Table 1.

AE activity, accumulation rate of the total amplitude, the number of AE pulses, or the total amplitude of AE pulses accumulated at the stage of uniform destruction can be used as an informative parameter ξ.

Defective samples have short or absent area of kinetically heterogeneous destruction. The amplitudes of the AE signals increase after the excess of the initial loading. This effect is interpreted as a demonstration of the scale effect: large structural elements are less durable and collapse after the first loading and the destruction of the remaining smaller elements is accompanied by the transfer of less energy. A further increase of amplitude is also associated with an increase of stresses where smaller but more durable structural elements are also destroyed. The dependence of the AE parameters of reloading samples patterned on these positions with idealized variants of the fracture process is shown in Fig. 4.

Table 1. The correlation of the state of the material structure and 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
		Spatioal	Kinetic	Energy	
Destructive (weak)	Delocalized fine dispersed heterogeneous	++*	++	++	Fall of AE activity and AE amplitude before final destruction, DRT**** variation, Kaiser effect
Without stress raiser	Delocalized fine dispersed heterogeneous	+**	+	+	Decrease of AE activity and AE amplitude, variation of DRT, Kaiser effect
	Delocalized fine dispersed homogeneous	+	–***	–	DRT variations, the Felicity effect, the ability to assess the concentration-kinetic strength AE parameters
With stress raiser	Localized fine dispersed heterogeneous	–	+	+	Decrease of activity, AE amplitudes, DRT invariant, Kaiser effect
	Localized fine-dispersed homogeneous	–	–	–	DRT invariant, the ability to assess the strength indicators
Increase of stress raiser	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, increase overlap ratio

*«++» is increased heterogeneity;

**«+» is significant heterogeneity;

***«–» is insignificant heterogeneity;

****DRT is the difference of the receiving time of ae signals to the registration channels.

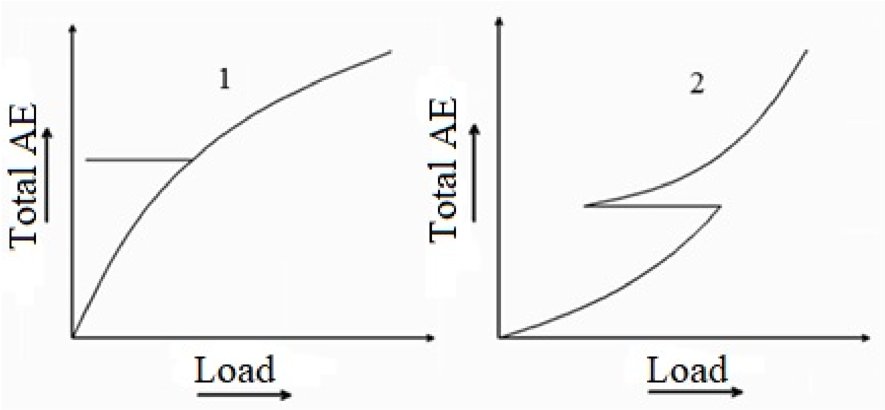

Fig. 4. Dependence of AE parameters of a reloading material on idealized variants of kinetically heterogeneous (1) and homogeneous (2) destruction

Real material is destroyed under time-dependent strength heterogeneity. The degree of heterogeneity gives the information about the condition of the object: the course of the process of kinetically heterogeneous destruction indicates a safe state of the object and the course of the process of homogeneous destruction, in contrast, indicates the presence and development of a dangerous defect. It is possible to estimate this degree based on the basis of imitation computer simulation determining the value of the ratio of the parameters of the function $\Psi(\omega)$.

The ratio of the parameters ω_0, ω_1, ω_2, σ, μ 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 $\omega_2/\omega_1 > 1$; $\omega_2/\omega_0 > 1$, for the samples made without distortion of the structural-stress state or with «sharp» stress concentrators the ratios were $\omega_1/\omega_0 < 1$, $\omega_2/\omega_0 < 1$, $\sigma_3 < \mu$; samples with high heterogeneity and immature structure are characterized by the values $\sigma_3 > 10\mu$, $\omega_2/\omega_1 > 10$; $\omega_2/\omega_0 > 10$ (Figs. 5, 6).

The physical meaning of these ratios of the parameters of the function $\Psi(\omega)$ is also revealed by comparing with other indicators of heterogeneity and in particular, according to the results of experimental data processing obtained during AE testing of welded samples of various degrees of surface layer processing where most of the geometrically heterogeneous elements are located. In particular, there was a good correlation of the ratio ω_2/ω_1 with the removed surface area of the overlap welds (Fig. 7 a-d, Table 1) and ring welded samples (Fig. 7e, Table 2). The results of the study indicate the connection between the parameters of the function $\Psi(\omega)$ and the area of the most structurally inhomogeneous region of samples of welded joints.

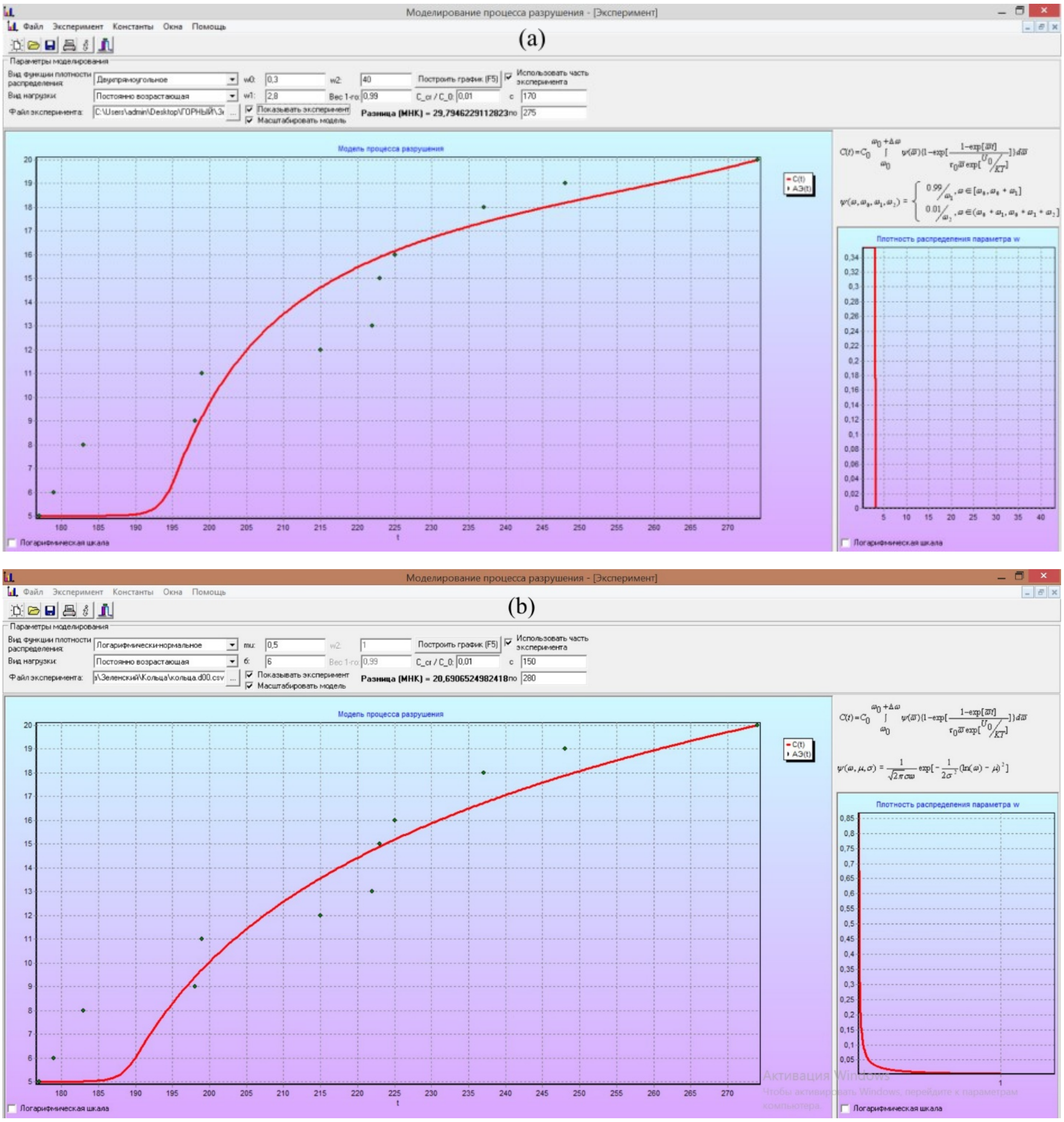

Fig. 5. Screenshot from the program showing the modelling of the destruction process and the distribution density of the parameter ω' described in [6]

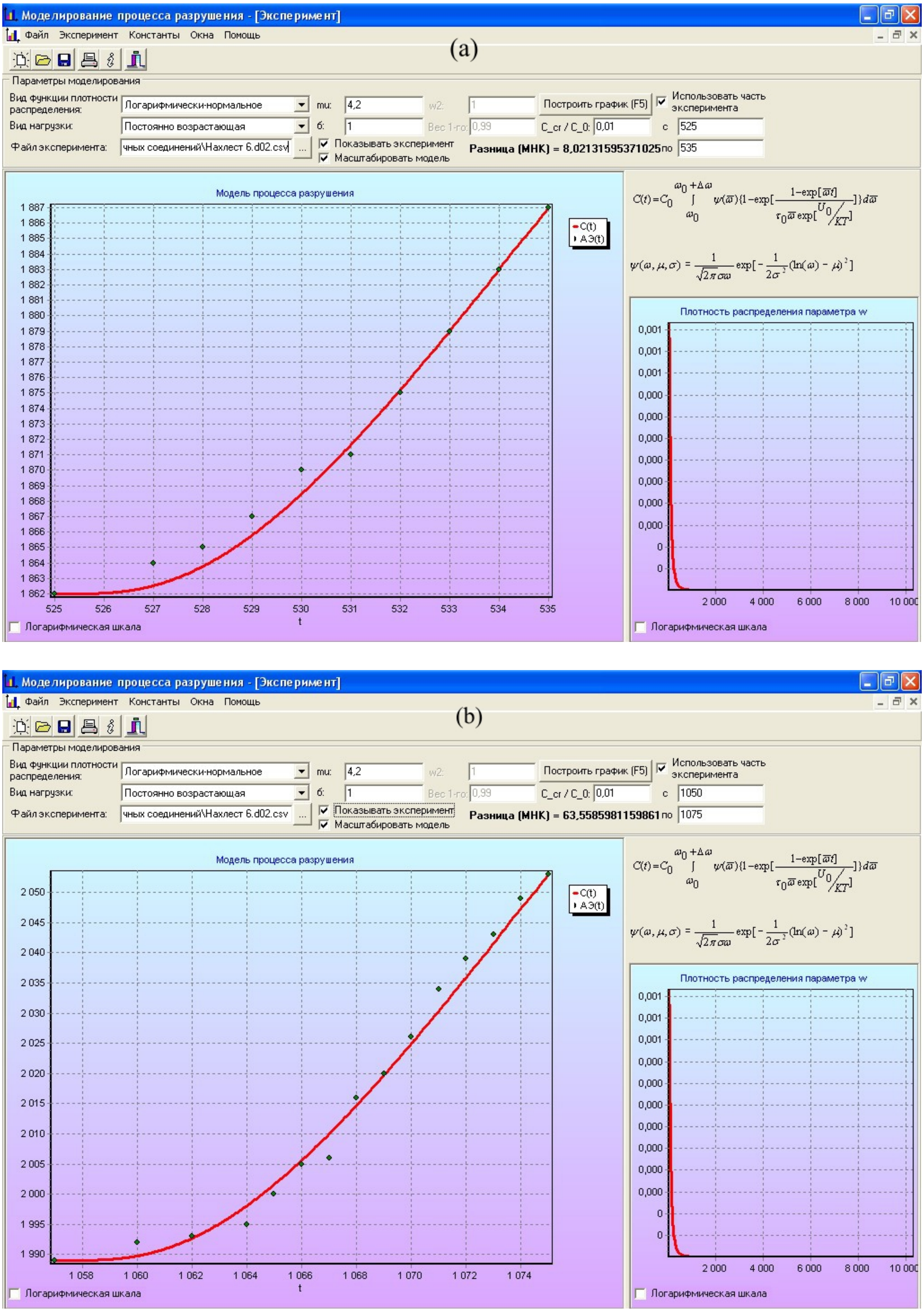

Fig. 6. Screenshot from the program showing primary (a) and second (b) loading under 45 kN a welded specimen without holes and with a crack, fracture is homogeneous ($\mu > \sigma_3$), the Kaiser effect is not manifested

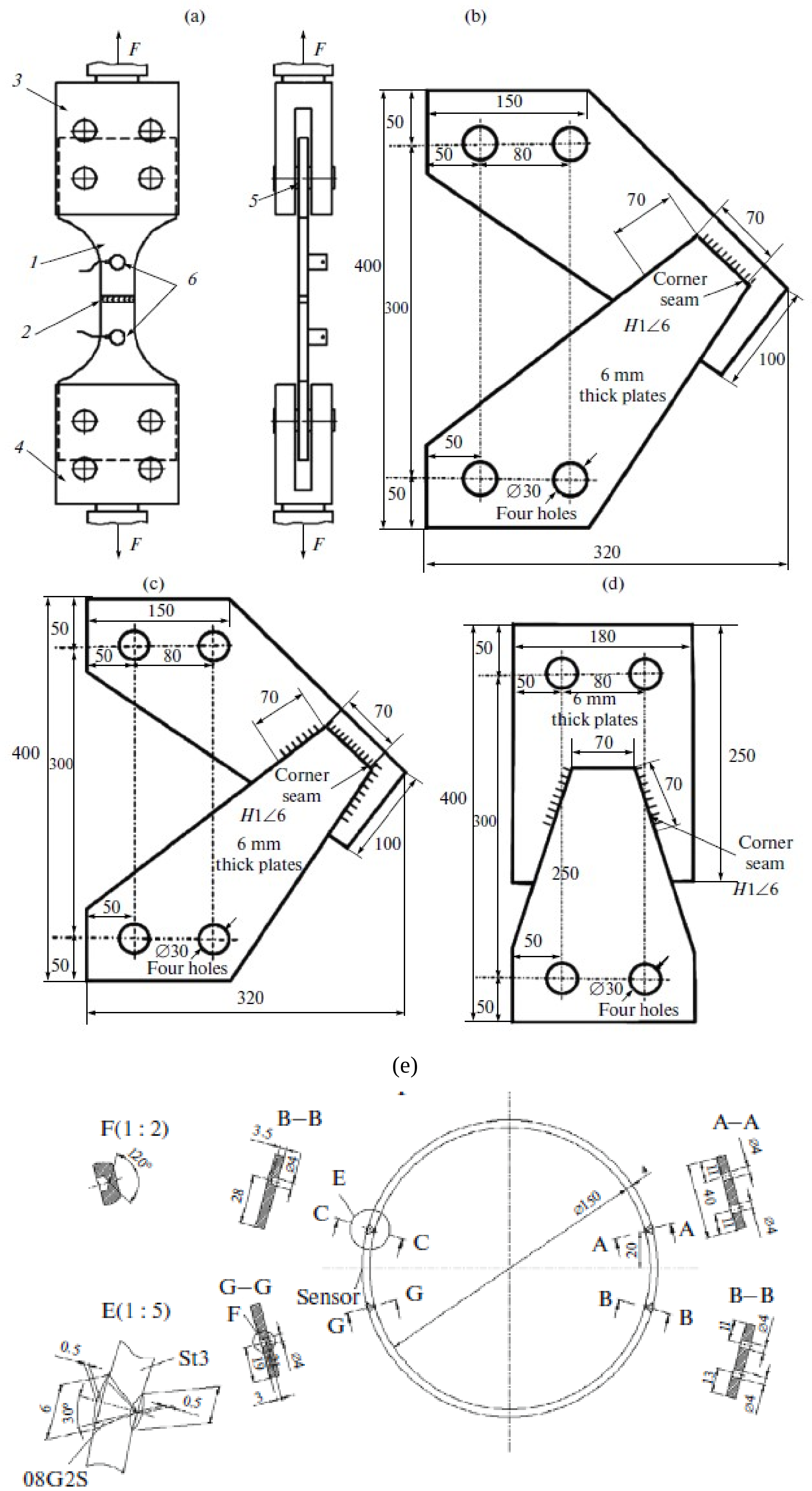

Fig. 7. Test samples with different shapes, types of loading and degree of imperfection: a) butt where 1- sample, 2-weld, 3-top grip loading device, 4-bottom grip loading device, 5-thumb, 6- Sensors of AE; and b), c), d) -lap-welded joints e) ring welded sample

Table 2. Correlation of the ratio of the parameters of the distribution density function $\Psi(\omega)$ with the area of the removed surface of the samples of overlap welded joints (Fig. 7 b, c, d)

Sample type	No sample	Defect type	Surface removed, mm^2	ω_2/ω_1
Front weld	1	-	0.000	2.833
	2	2 holes d6	56.520	3.000
	3	4 holes d6	113.040	24.000
	4	1 holes d6	28.260	4.667
Front weld and 2 flank welds	5	-	0.000	3.938
	6	6 holes d6	169.560	31.429
	7	12 holes d6	339.120	242.857
	8	3 holes d6	84.780	66.667
	9	3 holes d6	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 $\Psi(\omega)$ of ring samples (Fig. 6e)

№ sample	Defects	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 mm	0.92	0.875	0.89	19.6	268
4	2 blind holes outside: Ø2.4 and Ø3.2 mm; flaw 1 mm	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 mm and outside Ø3 mm	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		

According to the Table 2, the correlation of ratios $\sigma_3 > \mu$, ω_1/ω_0, ω_2/ω_1 between the values of the area of thermally untreated seams and maximum stresses is rather high which indicates the self-descriptiveness of the presented parameters. Thus, the fact of registration of non-uniform destruction is informative and indicates a safe state of the object. In this case, the estimation of the state of the object takes place at the stage of primary loading which allows reducing the resource and time costs during its study.

Using the model (1) it is possible to identify the various stages of the destruction of an object (Table 4). It is necessary to determine AE indicators of strength Y_{AE}, W_{AE}, described in

[6-10] to assess the resource at the stage of homogeneous destruction (following the heterogeneous) corresponding to the destruction of structural elements with ω values from the "bell" function Ψ(ω).

Table 4. Determining the stage of destruction and resource assessment

Stage	The name of the stage of destruction	Diagnostic sign of the destruction stage	Resource Evaluation Formula (T-moment diagnosis)
I	Delocalized fine heterogeneous	$d^2\xi/dt^2 < 0$ with $\sigma = 0$; $d^2\ln\xi/dt^2 < 0$ with $\dot{\sigma} = 0$; $dk_{AE}/dt < 0$ ($dP_U/dt < 0$); $\omega_2/\omega_1 > 1$, $\omega_2/\omega_0 > 1$; $\sigma_3 > \mu$ DRT = var	$\tau^* = (1 \div 10)\ T$
I	Delocalized fine homogeneous	$d^2\xi/dt^2 = 0$ with $\sigma = const$; $d^2\ln\xi/dt^2 = 0$ with $\dot{\sigma} = const$; $dk_{AE}/dt = 0$; $\omega_2/\omega_1 < 1$, $\omega_2/\omega_0 < 1$; $\sigma_3 < \mu$ DRT = var	Time to localization $\tau^* = f(Y_{AE})$ or $\tau^* = f(W_{AE})$
I	Localized fine heterogeneous	$d^2\xi/dt^2 < 0$ with $\sigma = 0$; $d^2\ln\xi/dt^2 < 0$ with $\dot{\sigma} = 0$; $dk_{AE}/dt < 0$ ($dP_U/dt < 0$); $\omega_2/\omega_1 > 1$, $\omega_2/\omega_0 > 1$; $\sigma_3 > \mu$ DRT = const	$\tau^* = (0,1 \div 0,5)T$
I	Localized fine homogeneous	$d^2\xi/dt^2 = 0$ with $\sigma = const$; $d^2\ln\xi/dt^2 = 0$ with $\dot{\sigma} = const$; $dk_{AE}/dt = 0$; $\omega_1/\omega_0 < 1$, $\omega_2/\omega_0 < 1$; $\sigma_3 < \mu$ DRT = const	Time before the hub starts to grow $\tau^*=f(Y_{AE})$ or $\tau^*=f(W_{AE})$
II	Formation and crack growth	$d^2\xi/dt^2 > 0$ with $\sigma = const$; $d^2\ln\xi/dt^2 > 0$ with $\dot{\sigma} = const$; $dk_{AE}/dt > 0$ ($dP_U/dt < 0$); $\omega_1/\omega_0 > 1$, $\omega_2/\omega_0 > 1$; $\sigma_3 > \mu$ DRT≈invar	$\tau^* = (0,01 \div 0,1)\ T$
II	Plastic fracture	$d^2\xi/dt^2 < 0$ with $\sigma = const$; $d^2\ln\xi/dt^2 < 0$ with = const; $dk_{AE}/dt < 0$ ($dP_{\Delta t}$ / dt < 0); $\omega_1/\omega_0 < 1$, $\omega_2/\omega_0 < 1$; $\sigma_3 < \mu$ DRT≈invar	$\tau^* = (0,01 \div 0,1)\ T$

Determining the parameters of the model is the most difficult because it is the most abstracted and requires in detail a reasonable acceptance of additional conditions that remove unnecessary uncertainty. The greatest number of papers in one form or another is devoted to finding the connection between the parameters in (1) based on the solution of the dynamic problem of the theory of elasticity. The search is complicated when taking into account the anisotropy of elastic properties, leading to uncertainty in the value of the coefficient $k_{AE}C_0$, reflecting the originality of the results of AE measurements and dependence on the type of object being diagnosed, its shape, size, type of defects, manufacturing technology, type of direct state, equipment, interference, the method and quality of mounting sensors, the gain of the measuring path of the AE system and its oscillations, the distance of the sensor to the AE source and other factors destabilizing the relationship of the AE parameters to the degree of the danger defect or strength characteristics of the object of control.

To reduce the degree of influence of these factors, the stabilizing values of the k_{AE} conditions of the AE measurements are formulated, which consist in ensuring at the time of the AE control of:

- the stability of the controlled volume of the diagnosed object;
- the stability of the gain and the thresholds of discrimination of the measuring system of AE;
- the stability of the characteristics of the energy or amplitude distribution of AE signals;
- the similarity of diagnostic and working loading of the diagnosed object;
- the constant speed of the diagnostic loading.

The approach to the processing of primary AE information makes it possible to formulate the energy, structural and time-dependent characteristics of strength according to micro- and nano-levels, to propose a number of valuable diagnostic AE parameter of the strength condition (Table 5) based on algorithms for non-destructive AE strength control. The practical use of these parameters (AE-indicators) is shown in [6–10].

Table 5. Models of the most valuable AE-indicators of the strength state of technical objects and their dimensions

AE-indicator	Micro-model	Nano-model	Macro-model	Dimension
X_{AE}	$d\ln\xi/dt$	$\gamma\dot{\sigma}/KT$	-	s^{-1}
Y_{AE}	$d\ln\xi/d\sigma$	γ/KT	$d\ln N_c/d\sigma$	Pa^{-1}
kY_{AE}	$d\ln\xi/dF$	$k\gamma/KT$	$d\ln N_c/dF$	N^{-1}
W_{AE}	$d\ln\xi/dK_H$	$\omega = \gamma\sigma/KT$	$\ln N_B - \ln N_{working}$	-

ξ is the primary parameter AE, $\dot{\sigma}$ is the stress growth rate in the material, $A_D = k_{AE}C_0/\{\tau_0 \exp[(U_0 - \gamma\sigma(t))/KT]\}$, K_H is the load factor (the ratio of the diagnostic load to the working load), $k=\sigma/F$ is the proportionality coefficient between the load and the nominal stress, N_c, N_B, $N_{c\,working}$ -parameters of the material fatigue curve.

Time to destruction at constant load ($\sigma = \text{const}$):

$$t^* \approx 10^{-15}\exp\left(\frac{U_0}{KT} - Y_{AE}\sigma\right) = \exp(M - Y_{AE}\sigma) = \frac{B}{\exp W_{AE}}, \quad (6)$$

where $M \approx \frac{U_0}{KT} - 34$, $B = \exp M$.

Strength limit:

$$\sigma_B \approx \frac{M}{Y_{AE}}. \quad (7)$$

Load of destruction:

$$F_{pn} = \left(\frac{U_0}{KT} + \ln\left(\frac{\tau_0 C^*}{C_0 F_p' kY_{AE}}\right)\right)/kY_{AE}, \quad (8)$$

where respectively, F_p' is the rate of growth of load when loading, $k=\sigma/F$ is the coefficient of proportionality between stress σ and the external load F on the specimen.

The number of cycles to destruction:

$$N_C = N_B/\exp W_{AE}, \tag{9}$$

where N_B is the material characteristic parameter, temperature and frequency of loading, determined by the stress-cycle diagram of samples of this material.

3. Experimental section

To solve the problem, the method of express control of strength materials has been developed, aimed at determining the resource-related parameters of the damage accumulation process in welded joints by means of rapid assessment of concentration-kinetic acoustic-emission strength indicators (Figs. 1, 2). The stage of fine destruction is divided into stages of non-uniform and uniform destruction (Fig. 9). The number of impulses N_Σ AE recorded at loading with a constant rate of stress growth at the stage of predictive uniform fracture is described by the time dependence:

$$N_\Sigma(t) = k_{AE}C_0KT\exp\left[\frac{(\gamma\dot{\sigma}t - U_0)}{(KT)}\right]/(\tau_0\gamma\dot{\sigma}) \tag{10}$$

and at the same time

$$\frac{d\ln N_\Sigma(t)}{\dot{\sigma}dt} = \frac{\gamma}{KT} = Y_{AE}. \tag{11}$$

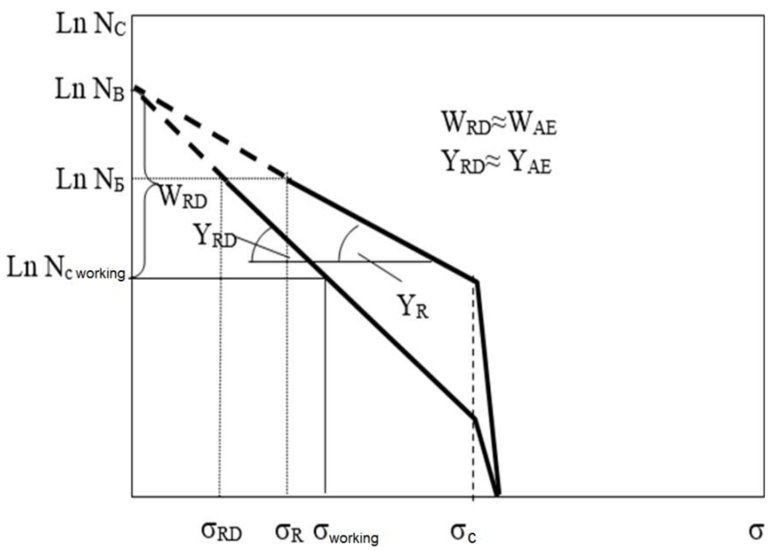

Fig. 8. Graphic interpretation of the connection parameters of W_{AE} and Y_{AE} with the resource N_C. σ_R, σ_{RD} – limit of endurance of the standard and the real part, respectively, $\sigma_{working}$, σ_c – working and critical stresses

The universality of the value of N_B at a constant temperature and loading frequency is justified by the connection with stable quantities that are included in the equation of the fatigue curve, expressed by the Zhurkov's formula, when:

$$N_C = \theta/\tau_{cycle}, \tag{12}$$

$$\lg N_B = \lg\left(\frac{\tau_0}{\tau_{cycle}}\right) + 0.43U_0/(KT), \tag{13}$$

where τ_{cycle} is the cycle period.

Comparison of the forms $Y_{AE} = d\ln N_\Sigma / d\sigma = \gamma / KT$ and $Y_R = d\ln N_C / d\sigma = -\gamma / KT$ and the values of these parameters obtained in figure 10 reveals their identity, suggests the inverse proportionality of the number of N_C cycles to destruction and the number of N_Σ registered impulses of AE which illustrates the validity of the hypothesis of linear summation of damages, which is actively used in the practice of designing engineering objects of mechanical engineering.

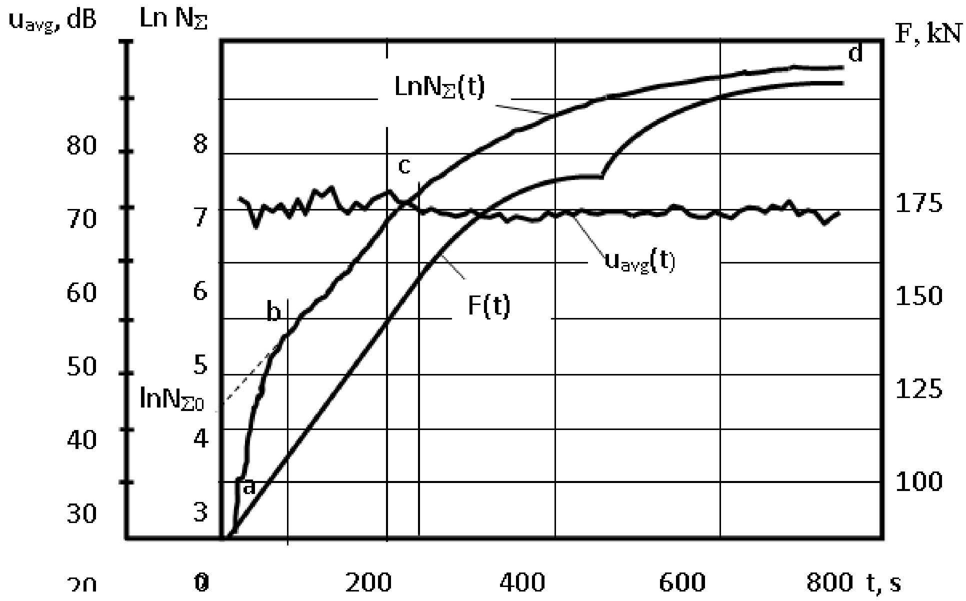

Fig. 9. The time dependences of the logarithm of the number $N_\Sigma(t)$ of AE pulses experimentally recorded during loading of samples (figure 7) with three characteristic stages of inhomogeneous fracture (a-b), kinetically uniform fracture (b-c) and plastic fracture (c-d), load F(t) and average amplitude $u_{avg}(t)$. AE strength parameters X_{AE}, Y_{AE}, W_{AE} are determined by step b-c. The values of the parameter Y_{AE} are consistent with values of the parameter Y_R (Fig. 10)

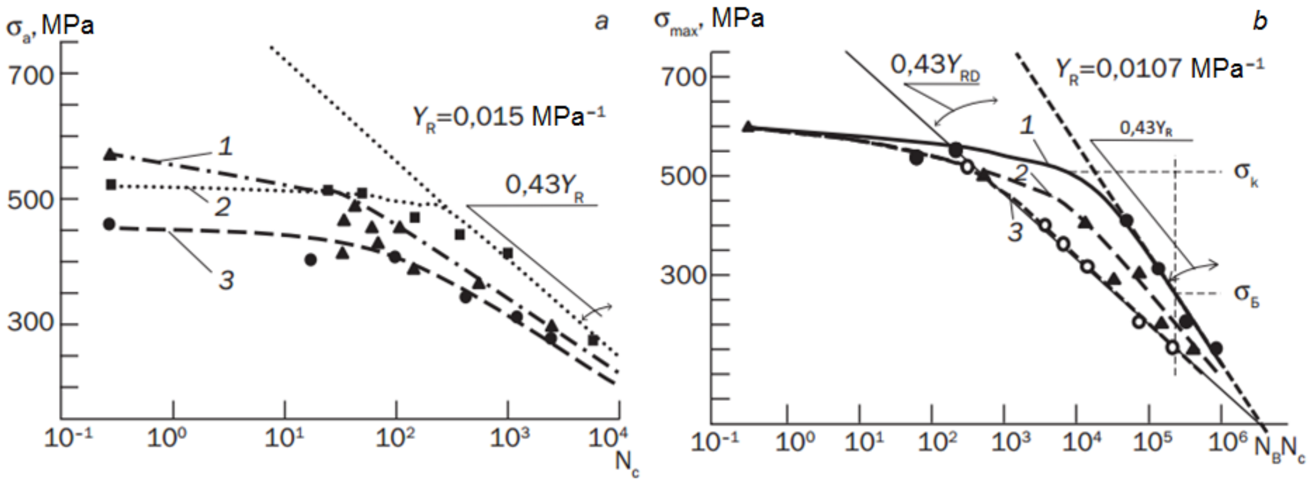

Fig. 10. Low cycle fatigue curves: a – results of low-cycle test of different zones of faultless tie-in welds of steel (1 – metal of corner weld; 2 – butt joint heat affected metal; 3 – base metal); b – results of low-cycle tests of butt joints of steel with a thickness of 20 mm (1 – quality connection; 2 – angularity of 8 mm at a length of 1 m; 3 – lack of penetration 4 mm)

Conclusion

1. The characteristics of strength, parameters of the process of destruction and AE materials depend on the result of simultaneously competition occurring in the material processes of destruction and plastic deformation of structural elements.
2. The resource of the majority of long-loaded materials, structures and facilities is

determined by the process of micro cracks formation, occurring in conditions of elastic deformation.

3. The destruction consists of following stages:
   - finely dispersed (scattered over the volume of the object or locally grouped in the defect area) accumulation of the concentration of micro cracks, consisting of kinetically inhomogeneous and homogeneous stages;
   - integrated localized discontinuity (formation or growth of a crack), flowing elastically or plastically.
4. Acoustic emission of elastically deformed materials is mainly associated with the process of micro cracks formation. The number of signals from plastic deformation of overstressed structural elements is relatively small. To reduce their destabilizing effect on the results of resource prediction, information filtering of signals should be applied to the selection of signals corresponding to the destruction of the most durable structural elements that determine the resource.
5. The usage of the micromechanical model of the destruction process and the acoustic emission parameters reflecting its temporal parameters allows us to propose a mathematical model of the strength heterogeneity, its quantitative criteria and a method for their evaluation, remove uncertainty in recognizing the state of monitored inhomogeneous objects, reveal the information content of the Kaiser effect and other signs of heterogeneous destruction.
6. Comparison of the parameters of the mathematical model describing the time dependence of the number of AE pulses and the parameters of the fatigue curve of samples of structural materials reveals their identity and confirms the hypothesis of linear summation of damage accumulated in the material at the stage of uniform destruction.

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