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DETERMINATION OF THE KINETIC STRENGTH CONSTANTS AND OF THE CRITICAL SIZE OF DESTRUCTION OF COMPOSITE MATERIALS ON THE BASIS OF RECORDING OF PULSE ELECTROMAGNETIC RADIATION DURING THEIR DESTRUCTION

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The thermofluctuation strength theory of S. N. Zhurkov [1] provides the basis of the kinetic concept of solids in a field of mechanical stresses.

According to this theory, the time until body destruction τ for stretching stress σ and absolute temperature T obeys the equation

$$\tau = \tau_0 \exp\left(\frac{U_0 - v\sigma}{kT}\right),$$

where U_0 is the interatomic binding energy, τ_0 is the period of atomic oscillations, and v is the activation volume.

A detailed study of the destruction process [2] has shown that cracks are generated in the body after time τ at a rate

$$\dot{N} = \dot{N}_0 \exp\left(-\frac{U_0 - v\sigma}{kT}\right). \tag{1}$$

A stationary accumulation of cracks ($\dot{N}$ = const) is realized only up to a certain boundary N^*, behind which follows the phase of accelerated accumulation, complete by rupture of the sample [2].

It has been established experimentally that the boundary value N^* obeys the concentration criterion

$$N^{*-1/3}/L = K^*.$$

Here K^* is a dimensionless constant, located for different materials within the limits from 2.1 to 6, L is the mean size of accumulation microcracks, and N^* is the number of cracks per unit volume.

In the case of time-varying stresses the time till destruction of a test sample can be determined tentatively, adopting the irreversibility condition of Bailey's damage accumulation [3], following in turn from the irreversibility of the destruction process during continuous loading:

$$\int_0^t \dot{N} dt = N^*. \tag{2}$$

It will be assumed that during the accumulation and fast propagation of microcracks during the destruction process there is local equilibrium of small volumes of the destroyed surface due to the fact that microscopically small portions of the system reach the equilibrium state substantially earlier than equilibrium is established between these small portions.

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Therefore, even though the whole set of particles of the newly formed surface of destruction is not found in equilibrium, one can refer to local equilibrium in microscopically small portions of the surface, characterized by their determination of temperature, chemical potential, and other thermodynamic parameters.

Taking these assumptions into account, the first postulate of thermodynamics of irreversible processes for a loaded body is written in the form

$$\dot{A} = \int_{(S_1)} \sigma_{ij} \dot{u}_i n_j dS_1 = \dot{U} - T\dot{S} + 2\gamma\dot{\Sigma} + \dot{\Theta} + \dot{K}, \tag{3}$$

where σ_{ij} are the components of the mechanical stress tensor at the exterior body boundary S_1, $\dot{u}_i$ are the velocity components of the displaced body boundary, T is the absolute body temperature, $\dot{S}$ is the rate of variation of the body entropy, $\dot{\Theta}$, $\dot{K}$ are the growth rates of energy of the secondary electromagnetic field and of the kinetic energy of body particles, $\dot{U}$ is the rate of change of the internal energy of the body, and $\dot{\Sigma}$ is the irreversible growth rate of the destroyed body surface.

According to Einstein's rule summation is implied in Eq. (3) over the repeated subscripts i, j (i, j = 1, 2, 3).

If during the generation process of new microcracks – surface destruction – condition $\dot{u}_i = 0$ is satisfied at the externally loaded body surface, i.e., u_i = const, Eq. (3) can be rewritten as follows:

$$\frac{dF}{dt} = -2\gamma\dot{\Sigma} - \dot{K} - \dot{\Theta} - S\dot{T} \tag{4}$$

(F = U – TS is the free energy of the body).

Due to the conditions $\dot{\Sigma} > 0$, $\dot{K} > 0$, $\dot{\Theta} > 0$, $\dot{T} > 0$, Eq. (4) indicates the direction of the thermodynamic destruction process – the formation process of a new destruction surface occurs in the direction of diminishing free energy. The state of thermodynamic equilibrium corresponds to a minimum free energy of the body, since dF/dt < 0. Starting from Eq. (3), and similarly to [4], we now introduce the specific volume destruction work A^* by the equation

$$A^* = \frac{A}{V}$$

(V is the volume of the destroyed body).

Following integration over time, Eq. (3) then acquires the form

$$A^* V = A = 2\gamma_{\text{eff}}\Sigma, \tag{5}$$

where A is the total work of the destroyed body, Σ is the total destruction surface, including the surface of microscopic cracks accumulated after the loading time, and γ_{eff} is the effective surface energy of destruction, including the unit surface energy of newly formed cracks, the energy of the electromagnetic field generated during the destruction process, heat losses, and other loss components, reduced to unity for the newly formed destruction surface.

Assuming, as in [4], that the quantities A^* and γ_{eff} are given for a given material, one can introduce the linear size d^* by the equation

$$d^* = \frac{\gamma_{\text{eff}}}{A^*}. \tag{6}$$

This size is naturally called the critical destruction size of the body. Using the equations introduced (5), (6) for the parameters A^*, γ_{eff}, and d^*, the critical destruction size can be provided with a specific physical meaning.

Indeed, since a microcrack of radius r liberates from stresses a volume of body destruction of order $(4/3)\pi r^3$, the total destruction work is in this case

$$A = VA^* \cong \frac{4}{3}\pi r^3 N A^*. \tag{7}$$

Here N is the number of microcracks accumulated after the destruction time (including the fact that they form a major macrorupture surface).

The total effective destruction surface energy Γ is

$$4\pi r^2 N\gamma_{\text{eff}} = \Gamma. \tag{8}$$

Equating (7) and (8), one obtains

$$\frac{r}{3} = \frac{\gamma_{\text{eff}}}{A^*} = d^*.$$

Thus, the critical (or minimal) destruction size d^* depends on the mean size of the microcracks accumulated during the process of body loading. In turn, the microcrack size r is determined by the minimum size of structural inhomogeneity of the body, on whose boundary the generation of fast cracks is stopped and held back.

The parameter d^* of composite materials depends substantially on the structure, technology, filament sizes and other parameters, and, thus, can serve as a generalized characteristic of the material strength and structure.

The problems of the present study are the experimental verification of the reliability of finding the time until destruction of composites from condition (2), as well as the determination of the critical destruction size d^* and of the kinetic destruction parameters U_0 and v of different composite materials during their destruction by increasing rupture load $\sigma = \dot{\sigma}t$ (t is time, and $\dot{\sigma}$ = const is a constant loading rate).

An equation for estimating the time until rupture of a test sample is derived from (1) and (2) for $N_0 = N^*/\tau_0$. For given test conditions one obtains

$$\int_0^{\tau} \tau_0^{-1} \exp\left(-\frac{U_0 - \omega\dot{\sigma}t}{kT}\right) dt = 1.$$

For the current values of t and N, where N is the number of microcracks accumulated following time t, one similarly finds

$$\int_0^{t} N^* \tau_0^{-1} \exp\left(-\frac{U_0 - \omega\dot{\sigma}t}{kT}\right) dt = N,$$

whence, assuming

$$\frac{N\omega\dot{\sigma}}{N^* kT} \tau_0 \exp\left(\frac{U_0}{kT}\right) \gg 1,$$

we have

$$t = \frac{kT}{\omega\dot{\sigma}}\left[\frac{V_0}{kT} + \ln\frac{\omega\dot{\sigma}}{kT} + \ln\frac{N\tau_0}{N^*}\right]. \tag{9}$$

Equation (9) makes it possible to apply the method of least squares, with the known values of t_i and N_i during the process of microcrack accumulation, as well as the condition

$$\sum_{i=1}^{n}\left\{t_i \frac{U_0}{\omega\dot{\sigma}} - \frac{kT}{\omega\dot{\sigma}} \ln\frac{\gamma\dot{\sigma}}{kT} - \ln\left(\frac{N_i\tau_0}{N^*}\right)\right\}^2 \to \min_{U_0, \nu},$$

and then find, from Eq. (9) at $t = \tau$, $N = N^*$, the sample longevity under a load and compare the time until destruction calculated from Eq. (9) with that actually measured during sample destruction.

To determine the kinetic strength constants and the destruction parameters of composites we use a method based on the recording of pulse ElectroMagnetic Radiation (EMR).

From the literature sources it is well known that during the nucleation of cracks in solid dielectrics, including composites, one observes short pulses (from 1 to 100 μsec) of radio and light emission, resulting from the separation of charges at crack edges, electron emission, and the generation of high voltage in the crack cavity (up to 10^9 V/m) [5, 6]. The pulse

TABLE 1

Name of sample	$\gamma \cdot 10^{-27}$ m^3	$U_0 \cdot 10^{-19}$ J	t_{exp}, sec	t_{theor}, sec
Polyamide PAIS-104C with no thermal treatment	15,8±2,98	1,446±0,01	18	17,3
Same with thermal treatment	3,49±0,61	1,478±0,03	62	59,2
Glass Textolite TSP-85	4,52±0,58	1,468 ± 0,01	100	105,5
Glass Plastic № 173	25,5±5,67	1,422±0,03	15	14,2
№ 174	29,7±4,37	1,406±0,06	8	8,2
Phenoplastic	34,5±7,58	1,426±0,45	40	41,3
Layer-foamed material	167±32,2	1,430±0,01	68	65,8

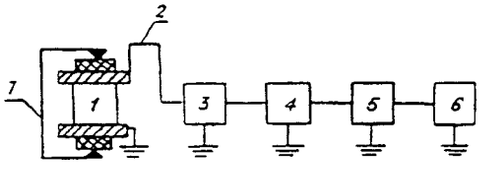

Fig. 1

amplitudes and durations depend substantially on the sizes of the cracks formed, their propagation rates, the material composition, and the material strengths [7]. During crack generation the EMR pulses are easily identified by their characteristic bell shapes, while in amplitude they exceed by several orders of magnitude the pulses resulting from the other electromagnetic effects and accompanied by deformation and destruction of dielectrics [4-7]. It is also necessary to note that the given method makes it possible to keep under consideration the destruction kinetics of nontransparent materials during the loading process. However, the method of handling observation results makes it possible to find at the early phases of destruction (until localization of the center of destruction) the binding energy U_0, the structurally sensitive coefficient v, and the critical destruction size d^*.

To verify the theoretical results presented above on samples of composite materials we selected the laboratory set-up shown in Fig. 1, where: 1) samples; 2) antenna; 3) amplifier-discriminator; 4) pulse counter; 5) timer; 6) memory oscillograph; 7) loading device BU-39.

The set-up makes it possible:

– to write down the values of the loading stress and of the deformation, and photograph the signal shape of EMR pulses accompanying sample destruction;

– to record the total number of radio pulses and determine their duration and amplitude;

– to deform samples uniformly with uniaxial compression by means of spherical indentors up to destruction of the samples investigated.

To reduce to a minimum the information distortion for the various transformations, the signal parameters and characteristics of the transforming systems must be consistent, i.e., it is necessary to carry out an optimal filtering of the whole input signal. For this purpose we applied to the set-up a layered selective filter with a steep cut of 6 dB/oct. To remove interference we used a high-frequency electric filter of RC-type and insulation from the network.

In the experimental process we recorded the frequency of pulse movement, their amplitude from 1.5 mV, and the spectral composition of their fill from 1 kHz to 50 MHz, visually observing and photographing the signal shape from 1 to 100 pulses. The study of the shape and variation of EMR signal parameters was carried out by photographic images with an ELT screen of an S8-12 oscillograph with a delay calibration sweep. As a loading device we selected a BU-39 sampling device, designed for complex determination of strength and deformation characteristics. The frequency of EMR pulse motion and their number were determined by means of a ChZ-54 electron counter frequency meter.

Figures 2 and 3 and Table 1 present the results of experimental estimates of the kinetic strength constants of composite materials of various structures.

TABLE 2

Name of sample	σ_p, MPa	$d^*, 10^{-4}$ m	d_{str}, 10^{-4} m
layered-foamed material	0,027±0,005	32±5	24±6
Penoplastic	0,160±0,062	7,3±2,1	11,5±1,8
Spherical layer 174	0,563±0,149	8,5±3,3	8,9±4,7
» № 173	0,667±0,094	5,1±1,6	6,3±3,5
Polyamide PAIS-104C C-with no thermal treatment	1,141±0,107	1,09±0,24	1,09±0,45
Glass textolite TSP-85	2,554±0,119	2,06±0,51	2,01±0,39
Polyamide PAIS-104C with thermal treatment	2,878±0,316	0,58±0,15	0,62±0,35

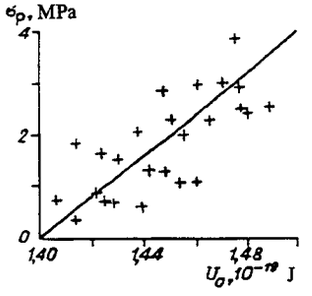

Fig. 2

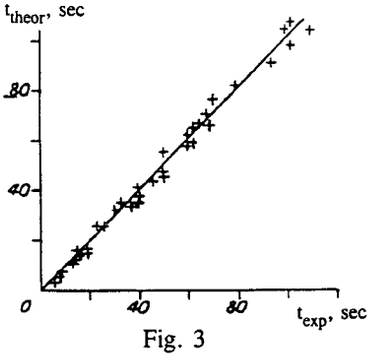

Fig. 3

Table 1 provides the average (over 10 values) kinetic constants for each type of composite material. The spread of values of activation energy for destruction U_0 and activation volumes v over the whole selection did not exceed 2.5 and 22%, respectively.

As follows from Fig. 2, the relation between the strength limit of composite materials and the activation energy of their destruction is nearly linear and obeys Eq. (1). The deviation from the linear calculated relation results from random oscillations with time of the mean value τ till destruction, as determined by the S. N. Zhurkov equation.

Figure 3 illustrates the dependence of the calculated t_{theor} of the predicted time (from the experimental t_{exp}) until destruction of composite materials for given loading rates. For complete agreement the points must by located on the bisector of the first quadrant (the line in Fig. 3). Quite satisfactory agreement of the two times is observed in Fig. 3. In all cases (see Table 1) the deviation does not exceed 5.5%.

Analyzing the data provided in Table 1, one reaches the conclusion that the activation energy of destruction U_0 depends weakly on the structure, properties, and technological regimes of production of composite materials, being the characteristic average energy of interatomic binding in the weakest link structure. The structurally sensitive coefficient v, reflecting the nonequilibrium loading of interatomic bonds, depends substantially on the extent of structural inhomogeneity and increases by dozens of times in sequence: strong homogeneous highly-porous composite materials. In all cases (see Table 1) the growth in structural inhomogeneity, fiber sizes, and so on, leads to substantial increase in the parameter v. The presence of a sharply expressed structural inhomogeneity leads to an increase in overexertion at the largest structural defects, reducing the strength of composite materials and leading to an increase in v.

The kinetic strength constants and the critical destruction size were determined on various samples of composite materials, which differed in the size of the original matrix, the time of thermal treatment, the sizes of structurally technological micropores, and the preparation technology (see Table 2).

Figures 4 and 5 and Table 2 present the results of experimental estimation of the critical destruction size of composite materials d^* and its relation to strength at stress σ_p and the structurally sensitive coefficient v.

As follows from analyzing the results obtained, the strength of composite materials decreases substantially with increasing critical destruction size. This well-known result can be specified quantitatively in the given case by introducing the critical destruction size for each group of composite materials. The critical destruction size correlates well with the mean size of structural inhomogeneity d_{str} of composites (see Table 2). The thermal treatment of composite materials, for example PAIS 104C, decreases substantially the critical destruction size and increases the strength and activation energy of destruction. The

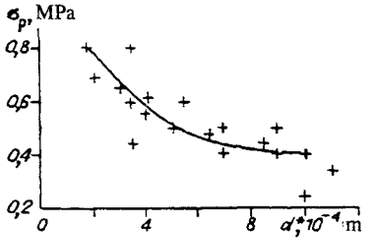

Fig. 4

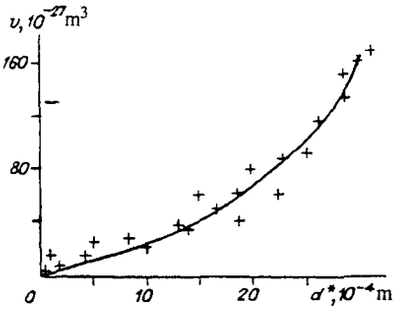

Fig. 5

structurally sensitive coefficient increases according to a power law with increasing sizes of structural material inhomogeneities (Fig. 5). Since v has the physical meaning of dimensional overexertion coefficient of interatomic bonds, then, naturally, one must observe an increase in that coefficient with increasing size of structural inhomogeneities and decreasing "live" cross section of the material, as verified by Fig. 5 and Table 2.

Determining thus the parameters U_0, v, and d^*, conclusions can be drawn concerning the structure of composite materials, their strength, and the effect of preparation technology on their mechanical properties.

From the discussion above it follows that the suggested recording method of pulse electromagnetic radiation during destruction of composite materials makes it possible to determine operatively the fundamental strength constants during phases of their preparation and testing, providing at the same time a correction to the preparation technology.

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