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ACOUSTIC METHODS

Applying Impact Loading for Revealing Cracks in Glass by Acoustic Emission Method

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Abstract—Results of studying regularities in the development of cracks in glass under impact loading using the method of acoustic emission (AE) and tensometry are presented. An experimental setup has been developed that provides a single dynamic action with further damping of elastic vibrations in a test object. It has been established that the relaxation of elastic stresses occurring near the crack after the impact is described by a logarithmic dependence. The parameters of the amplitude and time distributions of AE signals have been determined. A technique is proposed for dividing the total flow of AE signals into stationary groups with an exponential distribution of time intervals between the signals.

Keywords: acoustic emission, amplitude distribution of signals, dynamic tensometry, impact loading, stress relaxation, crack, glass

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INTRODUCTION

The possibility for selectively detecting defects that develop under loading is traditionally viewed as one of the main advantages of AE testing [1–3]. It is most promising in testing fragile materials, in which the hazardousness of defects largely depends on a stress concentration coefficient rather than their size. At the same time, loading is a sophisticated technological operation aimed at inducing such a stressed state in a material that provokes development of defects while preventing the complete failure of the structure. Vessels and pressurized apparatus are monitored in hydraulic or pneumatic tests. The stressed-strained state of parts, assemblies, and structural elements is created using dedicated loading devices [4]. When testing structures subjected to dynamic loads, creating conditions for the development of defects is a nontrivial task. Impact loading shows great promise for solving this task as it makes it possible to locally reproduce high levels of mechanical stresses and strains.

The regularities observed in AE caused by an elastic impact are described in detail in [5, 6]. However, in the detection of developing defects, of practical interest is the AE that accompanies the processes of crack development after oscillation damping. The thus-revealed regularities provide a basis for constructing systems to monitor facilities operating under dynamic or shock loads.

The aim of this work is to develop a technique for detecting cracks in brittle materials subjected to elastic impact loading using the AE method and dynamic strain gaging.

EXPERIMENTAL

Experiments were performed with 2-mm-thick flat samples with dimensions 200 × 300 mm, made of silicate glass (Fig. 1). The samples were placed horizontally on a damping substrate. A crack with a length of 5–15 mm was artificially created on the sample's longer edge. The samples were loaded using steel balls (strikers) 12 mm a diameter with a mass of 7 g, free falling from a height of 0.2–0.7 m. An aluminum tube tilted at an angle of 40°–60° to the sample surface was used to produce a directional impact. The point and direction of impact was chosen in such a way as to prevent repeated impact of the striker on the glass.

AE signals were recorded with the STsAD 16.03 system for digital acoustic-emission diagnostics (reg. no. 18892-10 in the State Register) [7] with a threshold detection level of 5 μV. Four AE transducers with a bandwidth of 0.1–0.7 MHz were mounted in the corners of the sample, a distance of 10 mm from the edge. The coordinates of AE sources were determined using planar ranging algorithms, based on the difference between the times of signal arrival at the AETs forming a rectangular piezoantenna.

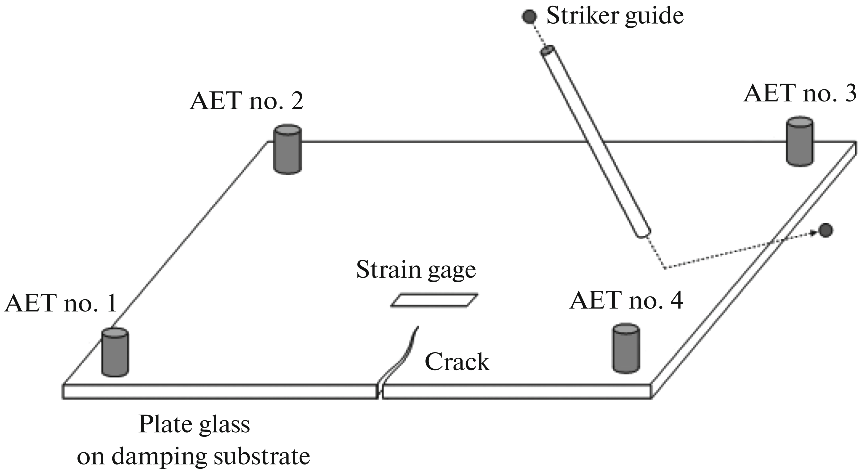

Fig. 1. Experimental setup for investigating AE under shock loading of samples; AET nos. 1–4 are AE transducers (AETs).

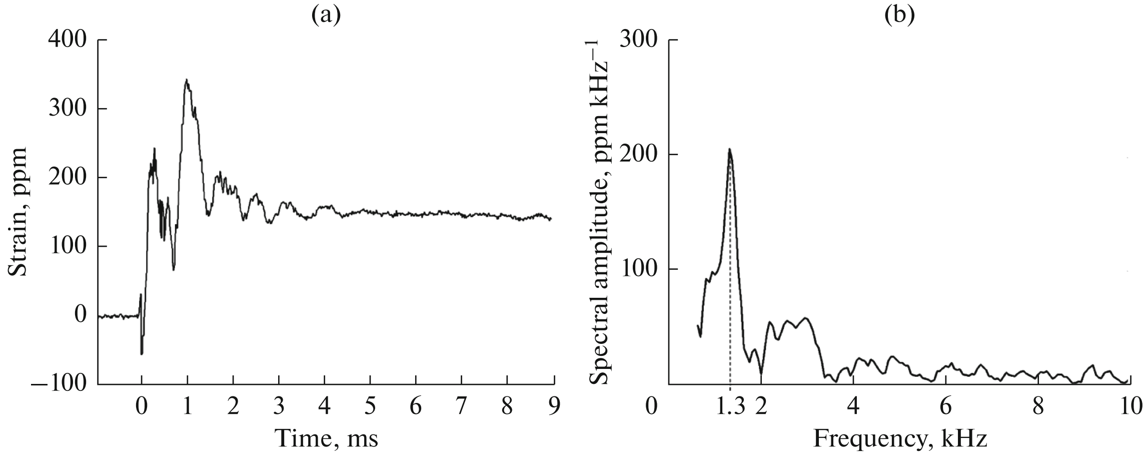

Fig. 2. Dependence of sample strain on time (a) and spectrum (b).

Deformations were recorded by the Dinamika-3 strain-gaging system (reg. no. 66973-17 in the State Register) [8] with a sampling frequency of 64 kHz. PKS-12-200 tensoresistive strain-gage wire transducers (reg. no. 37343-08 in the State Register) were glued to the sample surface perpendicular to the crack propagation direction.

EXPERIMENTAL RESULTS

For a period of 5 ms after an impact, time dependences of deformations exhibit oscillations (Fig. 2a) with a characteristic frequency of 1.3 ± 0.2 kHz (Fig. 2b). A residual strain of $\varepsilon = 100$–200 ppm caused by crack edges being displaced according to a mechanism of the longitudinal shear type is recorded after the impact. The time dependence of deformations is characteristic of transients of the second kind and is a superposition of the Heaviside function and damped harmonic oscillations. The characteristic decay time ranges from 2 to 5 ms, a period after which the amplitude of oscillations in the signal from the strain-gaging system falls below the level of instrumentation noise.

The diagnostic AE-system records continuous oscillations in the frequency range from 50 to 150 kHz, with their amplitude monotonously decreasing but remaining above the threshold level for 15–25 ms after the moment of impact. The system is incapable of capturing discrete AE signals within this time interval. The damping of elastic vibrations depends on the properties of the damping substrate beneath the sample and can be adjusted by varying the pressing force. After the oscillatory process is over, the relaxation of

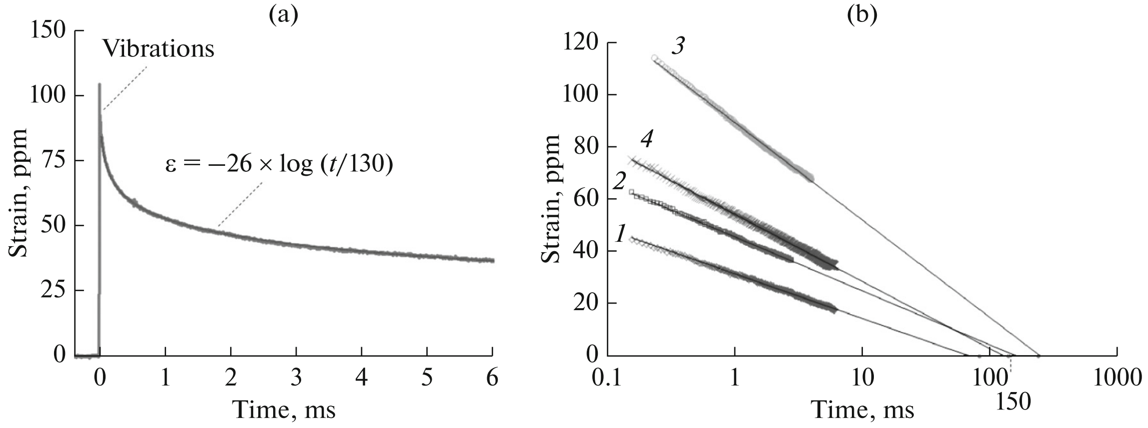

Fig. 3. Dependence of strain in glass with a crack on time plotted on linear (a) and semilogarithmic (b) scales for $t > 50$ ms (*1*–*4*) are the sequential numbers of impacts).

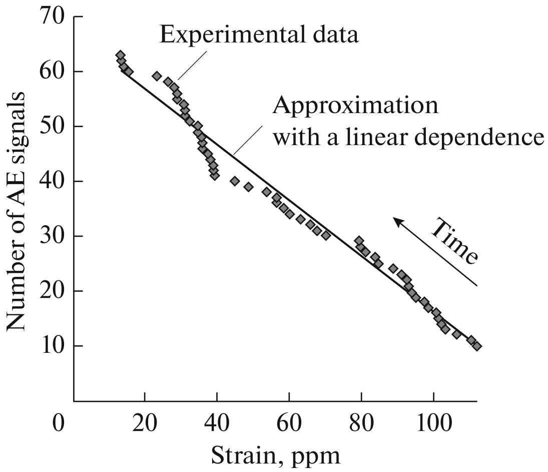

Fig. 4. Dependence of the number of AE signals on deformations after an impact within time interval from 0.03 to 25 s.

residual stresses, which monotonously decrease with time, can be observed in the signals from the straingaging system (Fig. 3a). The crack returns to its original state, with this process accompanied by the destruction of its edges, as indicated by the signals of discrete AE [9]. The dependence of strain on time is satisfactorily described by a logarithmic function of the form

$$\varepsilon = a \log\left(\frac{t}{\tau}\right), \tag{1}$$

where the parameters $a = 26$ ppm and $\tau = 130$ s are determined based on experimental data (see Fig. 3a) by least squares.

In all tests, the squared correlation coefficient, which characterizes the validity of approximation by the dependence in Eq. (1), was more than 0.998. Plotted on a semilogarithmic scale, the strain vs time graphs for four successive impacts (Fig. 3b) show convergence on the time axis at $\tau = 150$ s. The considerable time uncertainty in time τ, from 76 to 326 s, is associated with errors in extrapolating experimental data from the domain of 0.1–10 s to a fairly remote region of 100–400 s on the time axis.

The logarithmic dependence of strain on time can be justified in the framework of the kinetic theory of strength based on the well-known formula of A.V. Zhurkov [10]. Deformations relax by successive destruction of asperities on the contacting surfaces of the crack. The resulting AE is described by the micromechanical model [11], in which the number of AE signals is proportional to the number of collapsed structural elements in the material, which are the asperities on the crack edges. The relationship between the number of signals and deformations (Fig. 4) is of a correlation type ($R = -0.98$); it is satisfac-

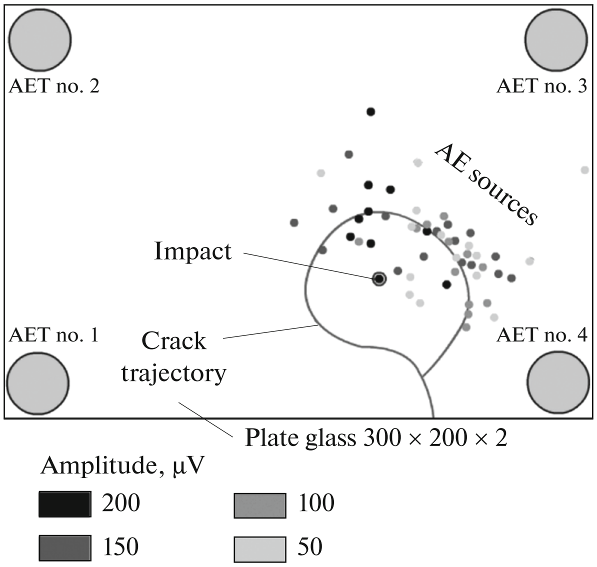

Fig. 5. Locating AE sources in sample with a crack using the STsAD-16.03 system.

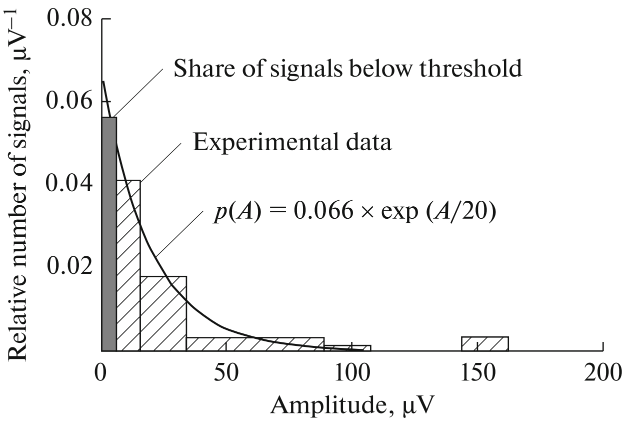

Fig. 6. Distribution of the relative number of AE signals over amplitudes.

torily described by a linear relation with a proportionality coefficient $k = -0.56$ ppm. Experimental data deviating from the straight line indicate a violation in the steadiness of the flow of AE signals.

Strain relaxation process lasts for tens of seconds, with discrete AE recorded during this time interval (Fig. 5). The point of impact is determined based on the first AE event with an absolute error of less than 10 mm. The AE signal corresponding to the impact is distinguished by its high amplitude (over 500 μV) across all channels in the AE system. AE events recorded at the stage of stress relaxation are localized along the crack. The uncertainty of the coordinates of the AE sources reaches 50 mm and is connected with overextended (longer than ~100 μs) leading edges of the signals and relatively small signal-to-noise ratio $K_{\text{sn}} = 4–10$ [12].

The amplitude distribution of the signals (Fig. 6) is described by an exponential distribution law with an average amplitude of 20 μV across the preamplifier input. Setting the discrimination threshold at $u_0 = 5$ μV provides for registration of approximately 70% of the total number of signals. The flow contains signals associated with processes occurring at the tip of the crack, their amplitudes being 100–800 μV, a value that is well in excess of the average value. The share of these signals varies from 10 to 12%, while the probability of the occurrence of such signals calculated based on the exponential distribution should not exceed 0.1%.

The overall AE flow reveals groups of signals separated by time intervals that significantly exceed the average time between signals within the group. To detect and identify the beginning and end of the groups

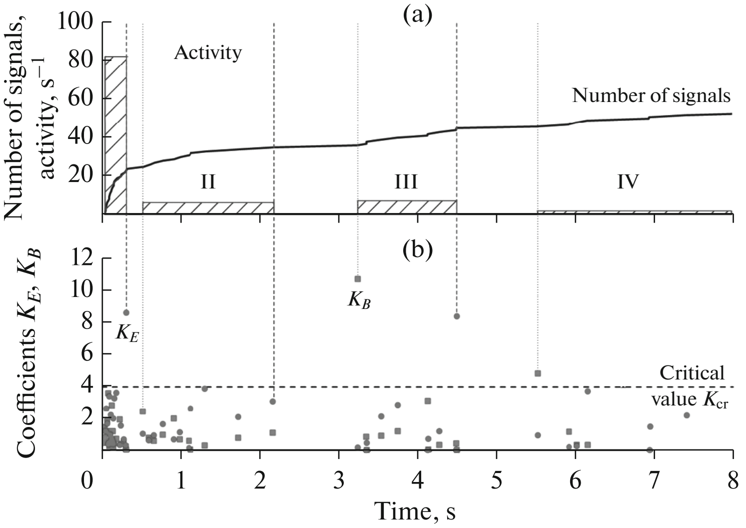

Fig. 7. Time dependence of the number of AE signals and the average activity of signal groups (a) identified based on the values of the coefficients of the ratio of time intervals K_B and K_E (b).

of signals, it is proposed to use the ratios K_B and K_E of durations of time intervals that can serve as indicators of the beginning and end of a group, respectively (Fig. 7b):

$$K_B = n\frac{t_m - t_{m-1}}{t_{m+n} - t_m}; \tag{2}$$

$$K_E = n\frac{t_{m+1} - t_m}{t_m - t_{m-n}}, \tag{3}$$

where t_m is the time when the m-th AE signal is recorded and n is the number of signals for estimating the average duration of the intervals.

The criteria for the beginning and end of a signal group are the coefficients in Eqs. (2) and (3) exceeding the critical value K_{cr}. The significance point, defined as the probability of the error of detecting an excess over the critical value in the absence of a group boundary, can be estimated using the hypothesis about exponential distribution of time intervals between signals within a group, viz.,

$$q = p\left(K_E, K_B > K_{cr}\right) = \int_0^{\infty}\lambda e^{-\lambda\Delta t_1}\left(\ldots\left(\int_{\frac{p}{n}\sum_{i=1}^{n}\Delta t_i}^{\infty}\lambda e^{-\lambda\Delta t_n} d\left(\Delta t_n\right)\right)\right) d\left(\Delta t_1\right), \tag{4}$$

where $\Delta t_1, \ldots, \Delta t_n$ are the time intervals between the signals, expressed in seconds.

The critical value of the coefficients of the ratio of durations of intervals between signals with a given significance level q and for an arbitrary n is determined by the solution of the expression in Eq. (4):

$$K_{cr} = n\left(\sqrt[n]{\frac{1}{q}} - 1\right). \tag{5}$$

The ratio of the standard deviation of time intervals between signals to their average value is $I[\Delta t] = 0.53$. Builo [13] showed that the parameter $I[\Delta t]$ is an invariant and can be used for assessing the nature of a signal flow. The invariant being distinct from unity indicates a violation of the hypothesis about exponential distribution of intervals between events and, therefore, a violation of the Poissonian type of the flow.

Using the proposed criteria, one can distinguish four groups in the overall flow of signals (see Fig. 7b), for which the values of invariant $I[\Delta t]$ are close to unity and vary within the range from 0.9 to 1.1, with the distribution of time intervals being described by an exponential distribution law, indicating the steadiness

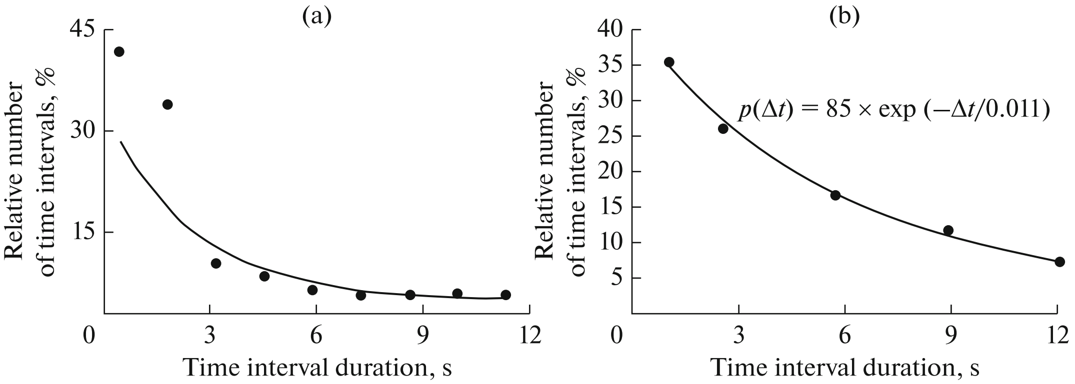

Fig. 8. Distribution of time intervals between signals over durations for the entire AE flow (a) and for group I (b).

of the processes. Groups I–IV and their average activities are depicted in Fig. 7a. The maximum average AE activity is observed for 300 ms after the impact, reaching 80 s^{-1}, followed by a drop in the activity to 1.5–6.0 s^{-1}.

The distribution of time intervals between all AE signals arising after the impact does not conform to an exponential law (Fig. 8a). Significant activity of AE signals in group I is due to a high value of the time derivative of strain (see Fig. 3a). The rapid relaxation of deformation destroys a significant number of structural elements in the material. The distribution of time intervals between AE events in group I (see Fig. 7) is satisfactorily described by the exponential law with a correlation coefficient of 0.98 (Fig. 8b). The performance of the STsAD-16.03 system does not allow recording all signals occurring after the impact, as the minimum possible time interval between two consecutive signals is 7 ms. AE signals in groups II–IV have low activity and, accordingly, smaller numbers of recorded signals due to a decrease in the rate of change of the strain level (see Fig. 3a).

ANALYSIS AND MAIN CONCLUSIONS

Impact loading of the object with a crack causes a residual elastic deformation associated with the displacement of the edges of the crack in the manner of longitudinal shear. Over time, the deformation decreases by a logarithmic law with a constant $\tau = 150$ s. This process is accompanied by the destruction of the edges of the crack, giving rise to discrete AE. The correlation-type ($R = -0.98$) dependence of the number of signals on strain is close to linear with the proportionality coefficient $k = -0.56$ mln. The amplitude distribution of the signals corresponds to exponential with the average amplitude across the preamplifier input equal to 20 μV.

Recorded AE is nonstationary; signals are emitted in groups with activities differing 10–50 times. Within a group, the value of invariant $I[\Delta t]$, equal to the ratio of the mean square deviation of the time intervals between signals to their average value, is 0.9–1.1, indicating the Poissonian nature of the occurring processes. Time intervals between AE signals within a group are described by an exponential distribution. Based on the ratio of the time interval between signals to their average value, a method has been proposed for revealing steady-state signal groups with a given level of significance q.

The developed AE-testing technique provides for detection of developed cracks in brittle materials under impact loading. The technique is based on recording discrete AE signals after elastic oscillations have decayed 25 ms after the impact for a period of 100–400 s, at the stage of relaxation of elastic stresses associated with the destruction of crack edges.

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