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Acoustic emission in the „honeycomb matrix–composite“ system under different heating conditions

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A complex system combining a honeycomb structure conjugated normally with a composite structure has been experimentally studied. For this purpose, the ideas of acoustic emission in solids are used (i.e., measuring the response in the acoustic range to external influences). But unlike traditional loading (compression or stretching) of the sample by external forces, a variation of the temperature field in which the sample is placed is used. A change in the temperature field over time (the rate of temperature change) generates temperature field gradients in the sample, which, in turn, they generate mechanical stresses in the sample, exciting acoustic vibrations in it. The dependences of the amplitudes of acoustic signals on time and on the rate of temperature change reveal a clear difference between a defect-free sample and a sample with a defect.

Keywords: honeycomb structure, composite, mechanical stresses, defects in structures, temperature field, acoustic emission.

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Introduction

The occurrence of radiation of acoustic vibrations in bodies under the influence of a load, known as acoustic emission (AE), is widely used to study defects in solids and their dislocation nature [1–9]. These methods make it possible to control phase transitions in crystals [5] and in inhomogeneous liquid media [6]. Moreover, in the last two cases, ultrasonic vibrations did not arise as a result of an external load, but as a result of the occurrence (or removal in the case of dissolution) of mechanical stress during a phase transition in the process of lowering the temperature. In these latter cases, the controlling factor is the change in temperature. AE methods are one of the effective methods for studying defects [7–9] and product quality [10,11]. The same methods are used to study cellular nanostructures of plants [12]. AE methods are used to study special, artificially created structures in the form of a honeycomb lattice [13–15].

The main approach to using the AE method is the need to load the testing object. When an external load, for example a bending force, is applied to the object under study, its defects, which are prone to development, begin to grow abruptly, causing local rearrangements of the material, which are sources of acoustic waves, and the rearrangement region itself is a source of AE [16, 17].

In the case of an artificial system „honeycomb matrix-external composite“ (Fig. 1), the presence of many interfaces can cause poorly controlled stresses and lead either to high attenuation of ultrasonic (US) oscillations or to a large number of additional sources of US oscillations. The interfacing of honeycombs with each other, their production and mating with a composite plate normal to the axis of the honeycomb structure does not exclude their imperfect execution. This suggests that honeycombs made from specially prepared paper may have a loose fit of the honeycomb walls to each other, i.e. the heterogeneity of such a fit, the heterogeneity of the interface of the honeycomb structure with the composite outer layer. All this creates difficulty and uncertainty even in defining the concept of defectiveness for such a structure. Also, in routine testing there is no way to mechanically bend or compress such a structure.

Meanwhile, changes in the temperature field over time and the resulting temperature gradients can change the stresses in bodies [18]. These changes can cause structural

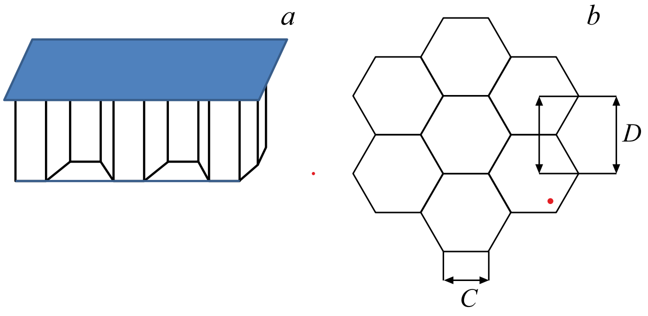

Figure 1. General view of the sample (a) and dimensions of the honeycomb cells (b). The honeycomb is made of specially treated paper.

rearrangements near defects prone to development, and, as a consequence, the phenomenon of AE Thus, manipulations with temperature and control of the resulting AE can serve as an independent method for studying a complex system of the „honeycomb matrix-external composite“ type. Note that changes in the temperature field in the samples make it possible to determine the temperatures at which phase transformations occur [5].

The paper [19] reported how a complex system of the „honeycomb matrix-external composite“ type responds to, generally speaking, uncontrollable temperature changes depending on the presence of a defect in the honeycomb structure. However, how the nature of these temperature changes (free or forced heating) affects AE signals remains unclear.

The purpose of this work is to find out how the presence of a defect in the in the system „cellular matrix–external composite“ will respond to the conditions of different modes (free and forced) heating of samples of various sizes.

1. Experimental procedure

1.1. Samples

The honeycomb structure consists of polymer paper (known as aramid paper) which is coupled to a carbon composite (Fig. 1). Elastic and strength properties in these structures are achieved by using impregnating compositions based on alcohol-soluble phenol-formaldehyde resins.

The honeycombs cells are hexagonal prisms with a height of $h = 28.5\,\mathrm{mm}$. The distance between the centers of the honeycombs cells is $D = 5.2\,\mathrm{mm}$, the edge width is $C = 3\,\mathrm{mm}$. Two types of samples were considered. The samples were prepared with the same dimensions as in the case of trial tests [19]. The first type of samples (hereinafter referred to as samples „*S* “, small sizes) have dimensions $100 \times 53 \times 30\,\mathrm{mm}^2$, and the second type of samples is large in size (hereinafter referred to as large sample „*L*“): $225 \times 95 \times 30\,\mathrm{mm}^2$. Large samples were selected so that their acoustic properties were the same as those of the largest product, i.e. preliminary measurements were carried out.

1.2. Hardware of the experiment

The changing temperature field as a result of heating the sample creates temperature gradients in it, which induce internal stresses. As a result, local rearrangements arise in the sample under study, which become sources of discrete AE. AE signals are supplied to the input of the acoustic emission transducer (AET), from where the signal goes to the input of the preamplifier and then to the analog-to-digital converter unit of the signal detection and processing system. In parallel with real-time AE monitoring, the sample temperature is monitored using a thermal imager with a frequency of 1 frame per 10 s.

During the experiment we used: low-frequency piezoelectric acoustic emission transducer GT-205, oil contact lubricant to increase the transmission coefficient of acoustic signals and acoustic emission transducer, ALP-01 preamplifiers, acoustic-emission measuring complex „A-Line 32D“, thermal imager InfReC R550Pro- D.

The use of such multichannel technology made it possible to carry out and maintain the same experimental conditions simultaneously for different samples This is important because it is impossible to provide the same temperature conditions every time, i.e. there are no two experiments in which the temperature conditions would be completely identical.

During registration, the A-Line 32D system had the following parameters:

- pre-amplification coefficient 34 dB,
- amplification 0 dB,
- intrinsic noise level 29 dB,
- discrimination threshold 32 dB,
- HPF — 30 kHz,
- LPF — 250 kHz.

In the experiments, the samples were initially placed in a freezer and cooled to a temperature of $T = -10^\circ$, after which one piezoelectric AE transducer was placed on the outer composite layer of each of them. In parallel with the reception of USW, the change in the temperature field (law of change T° C temperature over time t, $T = T(t)^\circ\mathrm{C}$) of the sample was recorded, and the rate of temperature change was determined. sing a thermal imager, changes in the temperature field were simultaneously recorded in samples of small (S) and large (L) sizes.

When considering the behavior of samples under conditions of temperature changes from negative values to room temperatures, it was necessary to provide for the condensation of moisture into the honeycombs cells. Since with a further increase in temperature from negative values and further, through the triple point of water and higher, ice crystals that appeared during condensation in honeycombs during evaporation to $0^\circ\mathrm{C}$, and then during melting, would make an uncontrolled contribution to the acoustic signal. To avoid such an effect of condensation in the honeycombs on the acoustic signal, the samples were pre-dried (including at high temperatures), then placed in a dry refrigerator at $-10^\circ\mathrm{C}$.

After manufacturing the samples and carrying out the entire complex of studies on defect-free samples, an artificial defect was introduced in each of them on one of the paper honeycombs — a vertical cut was made (parallel to the paper honeycomb). Then the entire set of tests described above was repeated for defective images.

Consideration of the influence of temperature changes on the AE of defect-free and defective samples was carried out in two different ways.

The first method involved natural heating of the sample as a result of placing a pre-cooled sample at room temperature. On average, this process can be characterized by the rate

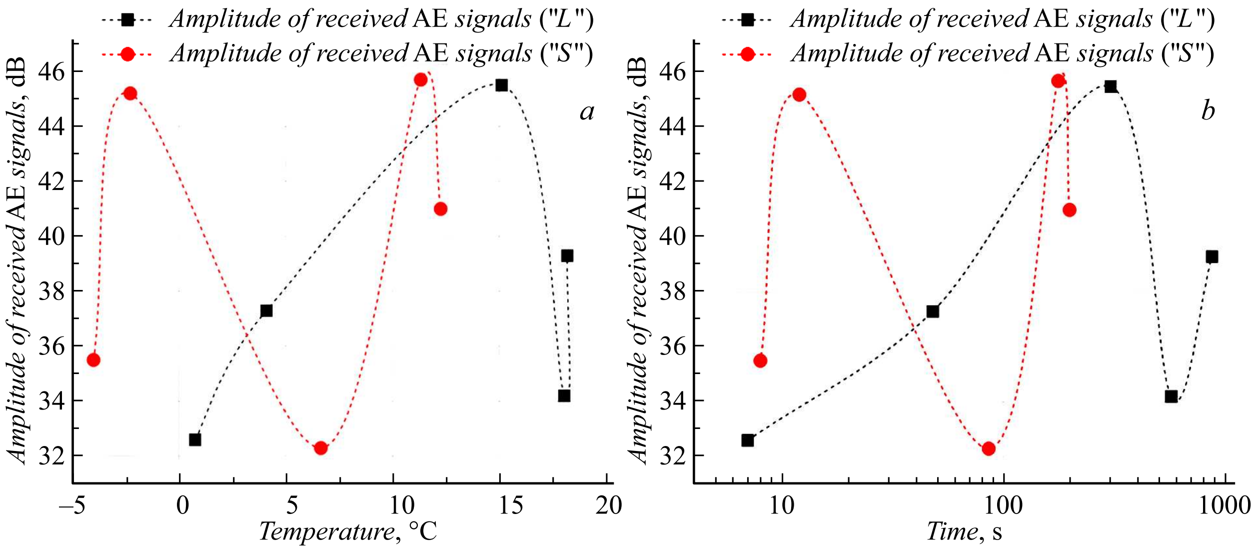

Figure 2. The dependences of the amplitude of AE signals arriving at the AET for defect-free samples on temperature (S) and on time (L) before the creation of artificial defects have a point character. The points are connected by dotted lines to distinguish the signals from different samples. Signals exist only at these points. The black dots correspond to the small sample. The red dots correspond to the large sample.

of temperature change. At the initial stage of heating, this rates the highest:$\Delta T/\Delta T \approx 0.1^\circ$ C/s.

The second method used forced heating. The essence of this approach was that the pre-cooled sample was heated with a halogen lamp, thereby increasing the rate of temperature increase.

In preliminary experiments, the following experiment was carried out: on the surface where it was planned to install the converter, a receiving AET was placed at various points, and on the reverse side, a second emitting AET was placed at one specific point. This operation was carried out in order to find out whether the installation point of the receiving transducer would affect the results of the experiment. It turns out that it did not. If the sample sizes were larger, the relative position of the AE source and the receiving PAT would influence the results. But in this work, the linear dimensions of the samples are relatively small. Nevertheless, for comparability of results, in each experiment the receiving PAT was placed at the same point.

The main characteristic of AE is the flow of acoustic pulses. The flow of acoustic impulses occurs under heavy loads. The restructuring of the structure is irreversible. In our case (in the case of thermal influences in the range from -10 to 30°C), the amount of energy obtained under such influence (see sectionc 3) turns out to be much less. Accordingly, the number of pulses emitted in the structure turns out to be small. In this case, it is appropriate to talk about the dependence of the amplitudes of acoustic signals on temperature and time, and not about the number of pulses per unit time.

2. Experimental results

All results based on experimental data for defective samples can be divided into two groups: small (S) and large (L) samples. Each time, a pair of samples consisting of a small sample (S) and a large sample (L) was placed in the same temperature field.

We are interested in the behavior of defective images. But to see where and how defectiveness manifests itself, it is necessary to compare their behavior with defect-free samples. Moreover, each step of the study began with a defect-free sample. Therefore, Fig. 2 shows for comparison the behavior of defect-free samples of different sizes during free heating.

Most of the incoming signals lie in the region of the highest rate of temperature change — initial, linear section: $0-15^\circ$C, and then when the temperature dependence transitions to saturation, the dependence of the amplitudes of the acoustic signals decreases (this dependence is similar to the curve shown in Fig. 3 for the defective sample, with the exception of a pronounced peak on it).

The first thing that the experimental results indicate is that there is a difference in the acoustic behavior of small and large images when they are placed in identical external conditions.

2.1. Free relaxation of the temperature of defective samples from negative temperatures to room temperature

We considered as samples of different sizes with an artificial defect (vertical cut parallel to the generatrix of the paper honeycomb), cooled to negative temperatures (-10°C) and

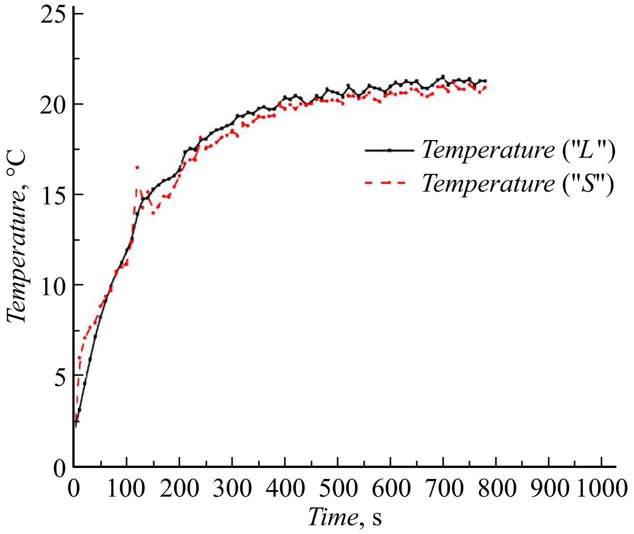

Figure 3. Free temperature relaxation from -10 to $+25^\circ$ on defective samples. On the red curve (large sample (L)) at 120 s a single signal appears (red dot in Fig. 4). Let's denote this pair of samples as Iα -samples.

placed at room temperature (+25°C), manifest themselves when the temperature relaxes from negative values to its room values at heating rate $\Delta T/\Delta t \approx 0.1^\circ$ C/s (Fig. 3)..

At the same time, the amplitude of the signals coming from the samples was recorded (Fig. 4). Here, in the presence of a defect, the active part of the signal oscillation occurs in the temperature range from 0 to $\sim 16^\circ$C. The rate of temperature change in this interval is $\Delta T/\Delta t \approx 0.1^\circ$C/s.

Variations in the law of temperature change $(T = T(t))$ and the creation of defects in a new pair of samples also lead to a change in the overall pattern of placement of acoustic signal oscillation points as a function of time.

As follows from a comparison of Fig. 3 and 4 with Fig. 5, the law of temperature change $(T = T(t))$ significantly changes the number of AE events. In one case (Fig. 3) the AE „picture“ is very poor. In another case (Fig. 5) — the number of acoustic pulses arriving at the system turns out to be significantly greater. Thus, the differences in the acoustic behavior of small and large samples are significant. Finally, on the next pair of samples (Fig. 6), another, new, picture of the dependence of the amplitudes of acoustic signals on time appears.

In the absence of temperature changes (at stationary temperature values in the range from -2 to $+25^\circ$C), acoustic signals are not observed.

2.2. Forced heating of samples from negative temperatures to room temperature

Next, an experiment was carried out with heating the defective samples using a halogen lamp (forced heating). In this case, a distance from the lamp of 1.5 m was chosen to ensure, on the one hand, sufficient heating, and on the other hand, uniformity of the heating spot (Fig. 7).

The rate of temperature change during forced heating increases twice as compared to free temperature relaxation. Forced heating leads to an overall final increase in the temperature of the sample to 30°C. In this case, the dependences „temperature–amplitude of the received signal“ and „time–amplitude of the received signal“ (Fig. 8) differ significantly from the same dependences for natural relaxation (Fig. 4). In particular, now the number of AE signals at the initial stage of heating increases (for a small sample), and for a large sample two signals appear (red line, Fig. 8).

These dependencies (Fig. 8) correspond to the law of temperature change (Fig. 9), and it specifies the nature of the change in acoustic signals depending on temperature and time.

At stationary temperature values in the range 0−30°C there were no acoustic signals.

However, when forced heating is applied, a change in the law of temperature variation (Fig. 10) significantly changes the dependence of the amplitudes of the acoustic signals of the samples. In particular, the small sample (S quickly comes to equilibrium, while the large one continues to oscillate. It should be noted that at the initial stage of heating for a small sample „S“ $\Delta T/\Delta t \approx 0.2^\circ$C/s, while for a large sample „L“ $\Delta T/\Delta t \approx 0.1^\circ$C/s.

The combination and comparison of three types of dependences: defect-free, defective with free relaxation, and defective with forced heating (Fig. 2−10) clearly reveals the influence of the forced heating defect and sample size on the AE signals and their sequence in time. In this case, the determining element in the characteristics of acoustic activity is the law of temperature change of the sample, $(T = T(t)^\circ\text{C})$.

3. Results and discussion

AE methods, usually used in practice, use external loads that can create significant restructuring of the structure, leading to the growth of defects already existing in the body, prone to development, as well as to the appearance of microdefects in the form of dislocations, cracks (for example, the energy required to create a dislocation is$\varepsilon \sim 10^8$ erg/cm^3 [20]). In this case, ultrasonic oscillations are emitted in the body under test. These types of loads also include methods for studying carbon fiber reinforced plastics using the AE method [21,22]. However, temperature changes in the sample that accompany its heating process may not always lead to significant restructuring of the structure. For example, under heating conditions, the amount of energy $\varepsilon \sim 10^2$ erg/cm^3 imparted to the sample (in our case) turns out to be at least several orders of magnitude less. Most likely, temperature changes in the temperature range under consideration (from -10 to 30°C) will cause reversible deformations and at the same time create a system response in the form of emission of

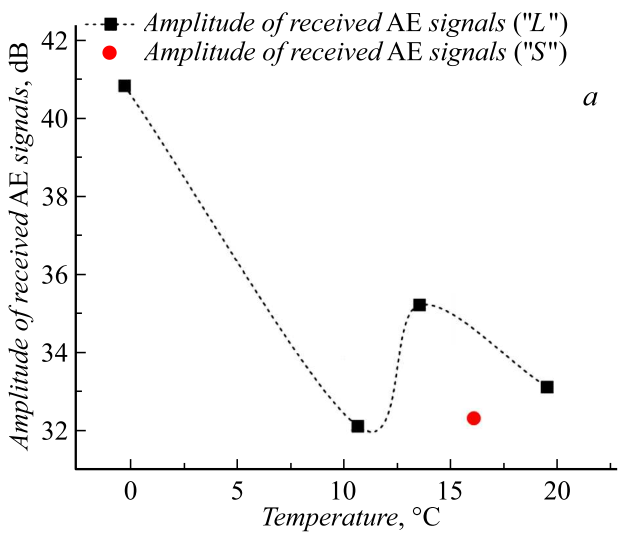

Figure 4. Dependences of the amplitude of AE signals incoming in the AER for defective samples on temperature (a) and on time (b) with free relaxation of temperature corresponding to the heating law Fig. 3. Here is also a point dependence of the signal amplitude. And the dotted line is shown only to indicate the difference between the signals from different samples. In this case, the signal from a larger sample (L)) degenerates into a single point (red point), i.e. during the entire observation period, only one signal appears and is recorded. This pair of samples belongs to α samples.

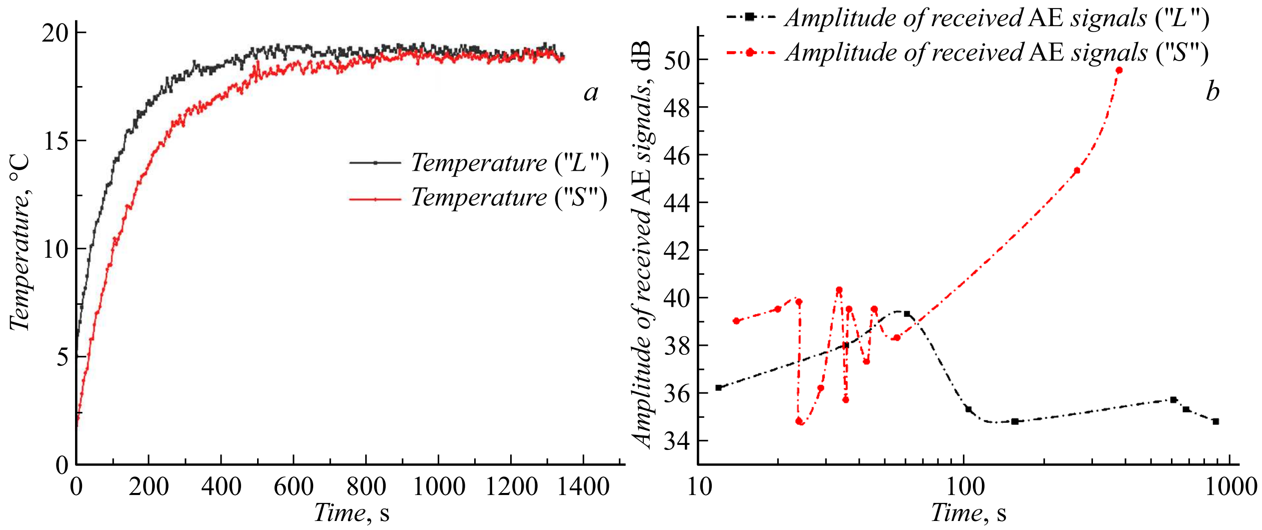

Figure 5. The law of temperature change (a) and the corresponding dependence of the amplitudes of acoustic signals on time (b) of small (S) and large (L) defective samples. Let's denote this pair of samples as caption β-samples.

ultrasonic vibrations in the sample. Let's demonstrate this situation [18].

(i) Our body under study can be compared with free energy

$$F(T) = F(T_0) - K\alpha(T - T_0)u_{ii} + \mu\left(u_{ik} - \frac{1}{3}\delta_{ik}u_{ii}\right)^2 + \frac{K}{2}u_{ii}^2, \quad (1)$$

from which the stress tensor is equal to

$$\sigma_{ik} = \partial F/\partial u_{ik}. \quad (2)$$

And from the condition of the absence of external forces $\sigma_{ik} = 0$ we obtain

$$u_{ii} = \alpha(T - T_0). \quad (3)$$

Here T — absolute temperature, T_0 — initial temperature value, no external loads, α — coefficient of thermal expansion of the body, K — modulus of compression, μ — shear modulus, u_{ik} — strain tensor, u_{ii} — its diagonal elements.

(ii) Heating (or cooling) of the body is associated with the supply (or removal) of heat $dQ/dt = T\,\partial S/\partial t$:

$$T\,\partial S/\partial t = \operatorname{div}\mathbf{q}, \quad (4)$$

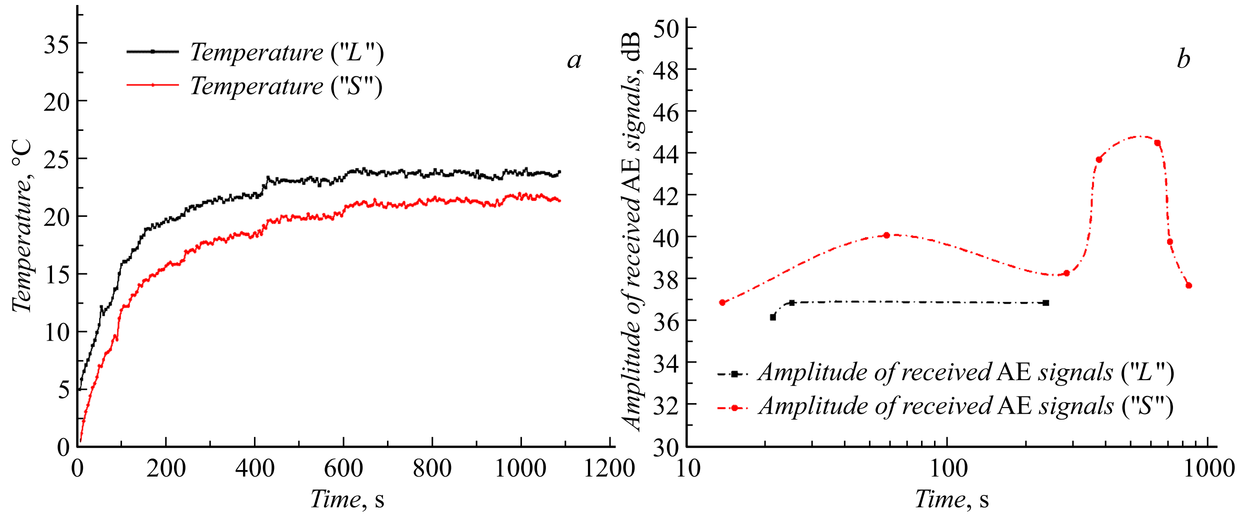

Figure 6. The law of temperature change (a) and the corresponding dependence of the amplitudes of acoustic signals on time (b) of small (S) and large (L) defective samples. Let's denote this pair of samples as caption γ-samples.

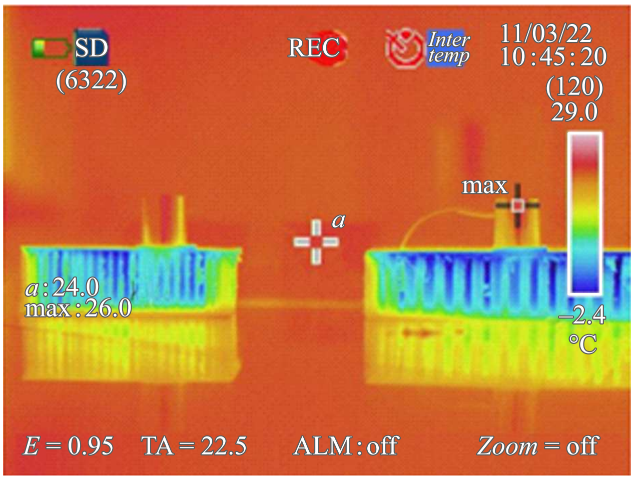

Figure 7. Control of external temperature, ensuring uniformity of the ambient temperature field for two different samples (blue color corresponds to a cooled sample, yellow color corresponds to room temperature).

where $\mathbf{q} = -\chi\nabla T$, χ — thermal conductivity, S — entropy.

Under conditions of ultrasonic vibrations in a solid body, the conditions of adiabaticity are satisfied, because during the period of vibrations between adjacent parts of the body, heat exchange does not have time to occur. And this means that the entropy of the body remains unchanged during the period of oscillation:

$$S(T) = S(T_0) + K\alpha u_{ii}. \qquad (5)$$

From the expansion of $S(T) - S(T_0)$ into a series in terms of the deviation $(T - T_0)$ we obtain

$$S(T) - S(T_0) = \partial S/\partial T|_{T=T_0}(T - T_0) = (C_v/T_0)(T - T_0). \qquad (6)$$

Here C_v is heat capacity at constant volume.

Then from (5) we obtain that the temperature difference gives rise to deformations causing a local increase in volume $(u_{ii} = u_{11} + u_{22} + u_{33})$:

$$T - T_0 = (T_0\alpha K/C_v)u_{ii}. \qquad (7)$$

And substitution (6) into (4) leads to the fact that the diagonal strain tensor u_{ii} changes in time, depending on the temperature change:

$$\partial u_{ii}/\partial t = \frac{1}{\alpha K T_0}(\chi\,\mathrm{div}\,\mathrm{grad}\,T - C_v\partial T/\partial t). \qquad (8)$$

Since $\mathrm{grad}\,T$ varies little along the sample, this relationship is further simplified

$$\partial u_{ii}/\partial t = -\frac{1}{\alpha K T_0}C_v\partial T/\partial t.$$

(iii) A change in time of the deformation tensor leads to the emergence of internal stress forces $\partial\sigma_{ik}/\partial x_k$, which lead to the equation of motion of an elastic medium with density ρ

$$\rho\, d^2u_i/dt^2 = \partial\sigma_{ik}/\partial x_k.$$

And taking into account the fact that $u_{ii} = \mathrm{div}\,\mathbf{u}$, after a series of transformations [18] we obtain the wave equation for the vector $\mathbf{u}$:

$$\partial^2\mathbf{u}_\gamma/\partial t^2 - C_\gamma^2\Delta\mathbf{u}_\gamma = 0,$$

where C_γ — speed of sound for longitudinal $(\gamma = l)$, or for transverse deformations $(\gamma = t)$.

Thus, in order to observe AE in a sample, the temperature distribution in it can be changed. The deformations resulting from this are small. And this does not imply the occurrence of significant rearrangements in the structure of the sample, but provides the emissions of acoustic vibrations. In

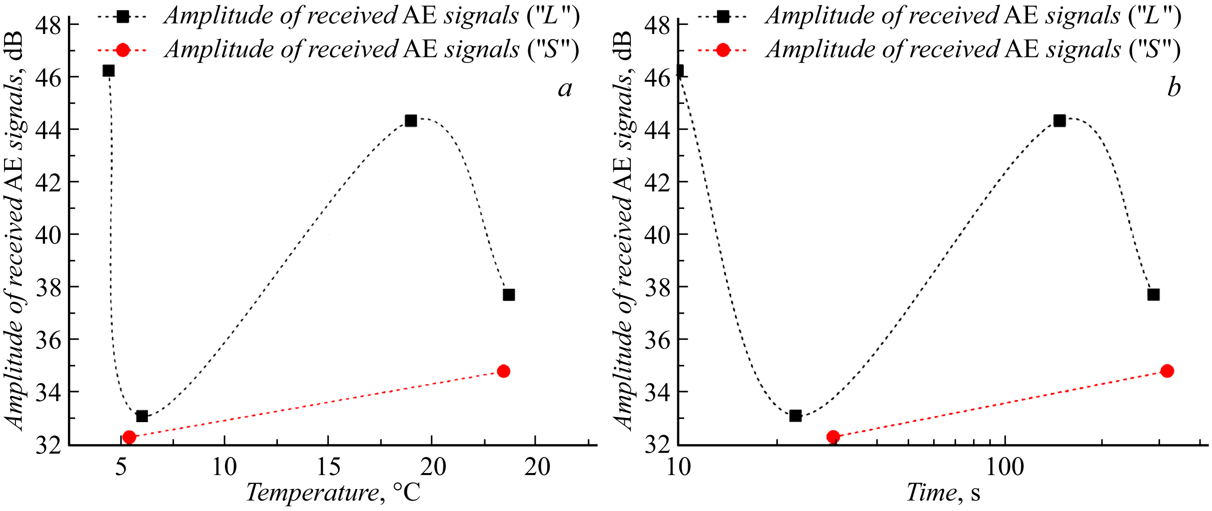

Figure 8. Dependences of the amplitude of AE signals incoming the AER for defective samples on temperature (a) and on time (b) during forced heating. α-samples.

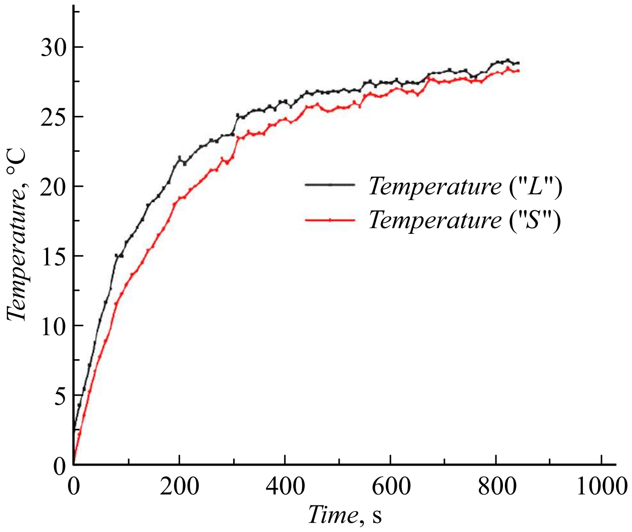

Figure 9. Law of temperature change during forced heating for Fig. 8.

addition, if there is a defect in the sample, then it causes the appearance of additional stresses. This, in turn, leads to the appearance of acoustic signals

One of the results of this work is the identification of the significance of variation in sample temperature with time on the excitation of AE for defect-free and defective samples. It turns out that with increasing temperature, a defect-free sample behaves more actively at the initial stages (generates a larger number of AE signals, Fig. 2) than a defective one (Fig. 4, 7).

In the case of defect formation, the dependence of the amplitudes of acoustic signals on the size of the sample is most clearly manifested. However, there is now no clear picture distinguishing a small sample from a large one. Each time, the difference in the size effect is revealed by comparing them. The reason for this is the $T = T(t)$°C law, which cannot be reproduced from experiment to experiment. Another such reason for lack of reproducibility is the occurrence of a defect that will always be different from the same defect in other samples.

Another important result was that the rate of temperature change during free heating (from negative temperatures to room temperature) turned out to be only two times less than in the case of forced heating. Such a weak dependence of the temperature change on the heating of honeycomb structures is apparently associated primarily with their high heat capacity. And forced heating here will not change the temperature much, just as long as the rest of the sample does not distribute excess heat throughout the sample. This situation is similar to first-order phase transitions, when the beginning of the transition and the end of the transition are determined by the latent heat of the phase transition, for example, melting (in the case of the transition „liquid to – solid“). Indeed (Fig. 8, 10), the first signal came when a small part of the honeycomb structure warmed up and additional stresses arose, and the last signal appeared when the rest of the sample reached the same temperature and became one whole.

In conclusion, it should be noted that for all samples of small sizes (five samples) and large sizes (three samples), the pattern of dependence of the amplitude of incoming AE signals on temperature and time during free heating shows similarity only in the simultaneous comparison of large and small samples in each $\alpha, \beta, \gamma, \delta, \varepsilon$- group. Those in each group of $\alpha, \beta, \gamma, \delta, \varepsilon$- samples, the presence of a defect is detected by simultaneous measurement of a large and small sample. Here are the results only for the α, β and γ groups of samples (these groups contain a complete set of large and small samples, the Iδ, ε groups are provided only with small samples and largely repeat the behavior of small samples from the α, β and γ groups).

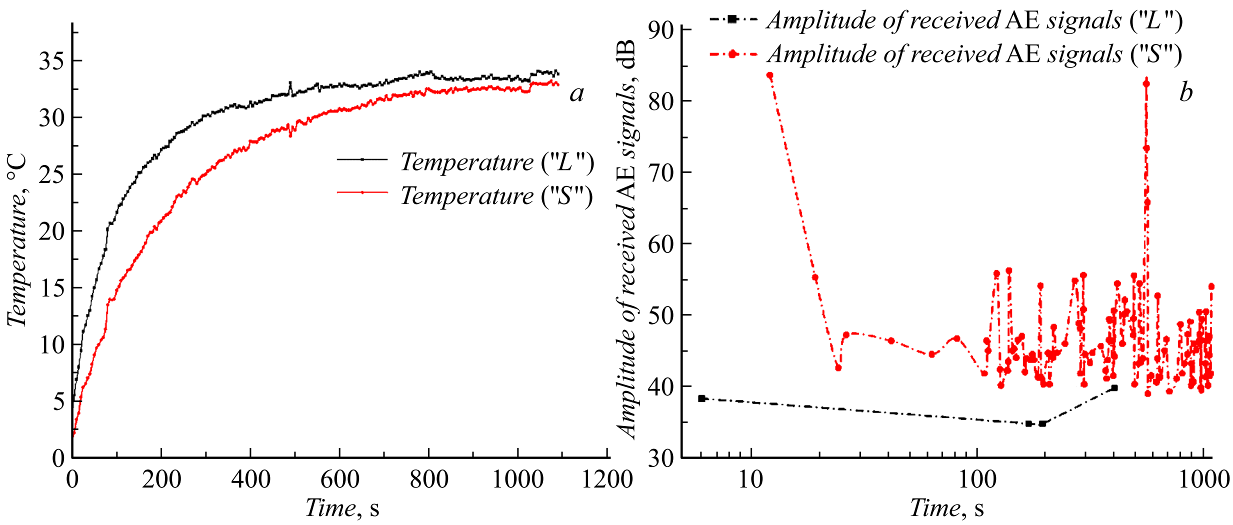

Figure 10. Law of temperature change (a) and dependence of the amplitudes of acoustic signals of defective samples of large (L) and small (S) sizes in time (b) β -samples.

Conclusion

Comparison of the dependence of the amplitudes of acoustic signals on temperature and time gives the following main results:

1) Identical honeycomb panels, differing only in geometric dimensions, in the absence of defects, have different dependences of the amplitude of AE signals on time.

2) The law of temperature field changes affects the total number of recorded AE pulses arising in the honeycomb structure. This indicates that either the average amplitude of the AE pulses or the spread of the amplitude around the average value is changing.

Thus, it follows from the experiments that there is no strictly stable picture of the dependence of the amplitudes of acoustic signals on the shape of the defect or the size of the defect and on the size of the samples. But in the absence of variation in temperature fields, there are no AE signals. AE signals arise when the temperature field varies and they differ in the presence of defects and allow defects to be detected.

Conflict of interest

The authors declare that they have no conflict of interest.

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