Features of the AE Testing of Equipment on Operating Mode

Dmitry CHERNOV [1], Sergey ELIZAROV [1], Vera BARAT [1], Igor Vasilyev [2]

[1]*INTERUNIS-IT LLC, Moscow, Russia; Phone: +7 495 3617673; e-mail: chernovdv@interunis-it.ru*
[2]*Blagonravov Institute of Machine Science, Russian Academy of Sciences, Moscow, Russia*

Abstract
Composite materials are very widespread in aerospace, reinfinery and chemical industries. The wide application may be explained by the improved mechanical properties -ultimate tensile strength, flexural modulus and small specific density.
The nondesctructive evaluation of the composite materials is an actual and complicate problem. Traditional ultrasonic, thermal and electromagnetic NDT methods have a limited application which is explained by anisopropic properties of the composite materials. This study focuses on the problems of acoustic emission arrising during the composite materials testing.
In the case of the composite materials AE testing has a set of specific features, for example, high AE activity even at the beginning of the structure loading, diversity of AE signals waveforms and spectra from the different AE source (fiber breakage, matrix cracking, destruction of the adhesive layer). Novel AE data registration method adapted for composite materials was offered in this sudy. This method takes into account the multiform and multiscale character of AE data. It allows to separate AE impulses from the different sources – fiber and matrix and as result - estimate the intensity of destruction for each component of the composite material separetelly. Authors also proposed improved criteria and improved location algorithm for the composite materials.

Keywords: AE,

Introduction

From year to year, composite materials find expanding applications in a different industries - aerospace, oil, machine building, and in medicine and construction. The main advantages of composites are high rigidity, specific strength and low weight. Despite all the advantages, composite materials have some drawbacks – the lack of methods for the nondestructive estimation and the low level of maintainability. Thus it is an urgent problem to ensure accident free operation of dangerous industrial objects made of composite materials, and its solution will allow an improvement of the reliability level of devices in service.

One of effective NDT methods within the limits of which such systems are implemented is the acoustic emission (AE) method. This method is highly sensitive and does not require surface scanning. Also, the AE method is quite universal and can be used to test both metal and non-metal objects. Furthermore, multilayer and complex structure of the test material has an effect on the diagnostic results to a lesser degree as compared with an ultrasonic or thermal testing method.

Destruction of Composite Materials

The initial step in solving this problem is study of destruction mechanisms in composite materials. The behavior of composites under loading is influenced not only by the presence of defects, but also by the characteristics of matrix and dispersed phase, the state of dispersed phase (fibrous or granular), the content of this phase in the composite, the direction of applied force, etc.

Methods of composites manufacture may also have a significant influence. The sizes and distribution of voids and inclusions, the degree of nonuniformity of fibers distribution, the state of adhesion between the levels are dependent on these methods [3,4].

Based on achievements of modern science in the field of AE testing of composite materials, it is necessary to identify the main types of acoustic signal sources occurring in the course of applying load of the specific kind. For example, Ono et al. [6] demonstrate the potentially possible AE sources occurring during destruction of a fiber-reinforced composite.

When the composite stretches in longitudinal direction, a damage accumulation model includes the stages of matrix destruction, adhesion layer destruction and fiber destruction. In the initial stages of loading the occurrence of AE sources is associated with brittle destruction of matrix. The process of matrix destruction is characterized by appearance of acoustic signals with characteristic high-frequency spectral components (up to 700 kHz) and large amplitudes, which reach values in excess of 55 dB [7]. The AE signals which appear with further increase in load can be associated with the adhesion layer destruction. Such sources are characterized by signals with amplitude from 60 to 80 dB. Further loading of composite will lead to the fiber destruction. The process of fiber destruction is characterized by acoustic signals, whose amplitudes can reach 100 dB or more [7, 8].

During application of shear loads, the following stages of composite destruction should be identified, i.e. matrix destruction and delamination. The initial stage of composite destruction during application of shear loads is the matrix cracking. AE sources occurring in the course of matrix destruction both at shear and at tensile loadings are characterized by acoustic signals with similar values of standard parameters. Further increase in loading leads to composite delamination. During delamination the sources of acoustic signals occur with amplitudes corresponding to the range from 50 to 70 dB. It should be noted that these signals are low-frequency, with a resonant frequency of about 100 kHz [7, 9]. Thus, based on the values of standard AE parameters and the known type of applied load it is possible to identify the stages of composite destruction and to create new criteria parameters for estimating the state of structures made of composite materials.

Results of Laboratory Research

To investigate the process of composite material destruction and to specify the diagnostic model, a series of experiments was carried out which involved compression and stretching of composite material reinforced with carbon fibers.

The first stage of research is study of destruction model using the AE method in the course of stretching (Fig. 1) of the composite specimen (Fig.2). Fig. 2 shows the specimen of polymer composite material (PCM) brought to failure using the AE method. The system A-Line 32D by the company "INTERUNIS" was used as equipment for recording acoustic signals.

Fig. 1 Stretching - tensile machine “INSTRON-250"

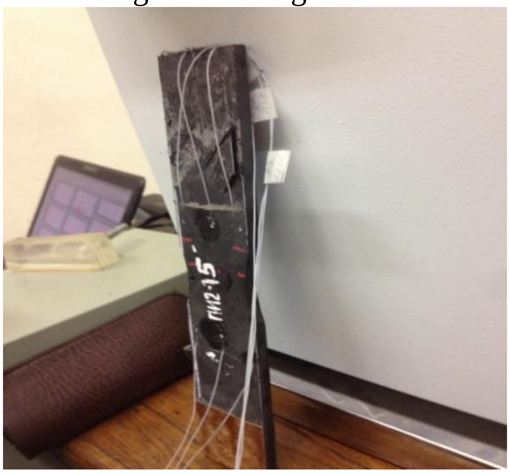

Fig. 2 Test specimen of PCM

In the experiment AE sensor GT200 were used with a resonance frequency of 165 kHz, as well as preamplifiers by the company "INTERUNIS" with a frequency bands of 25-500 kHz and a gain of 26 dB. Tests were performed according to a specially designed loading diagram (Fig. 3).

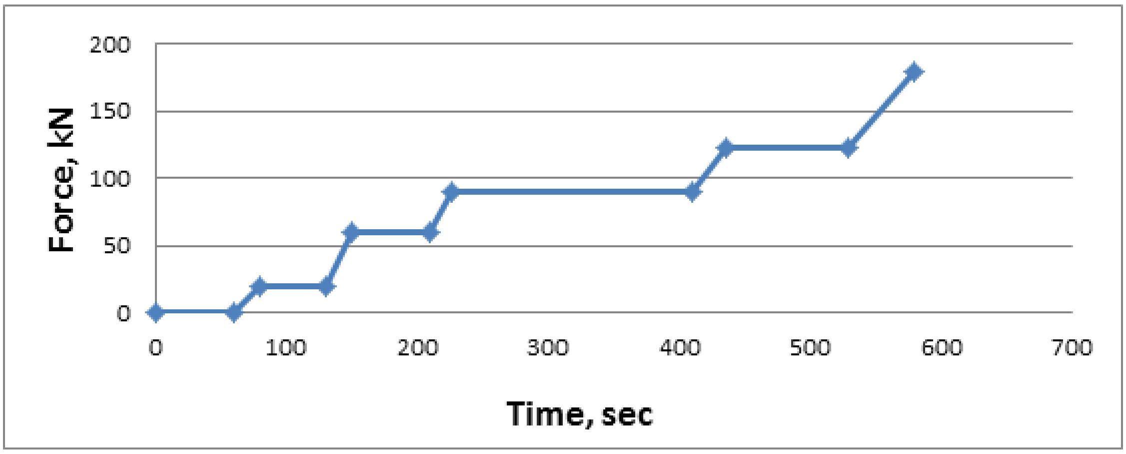

Fig. 3 Loading diagram of PCM specimen

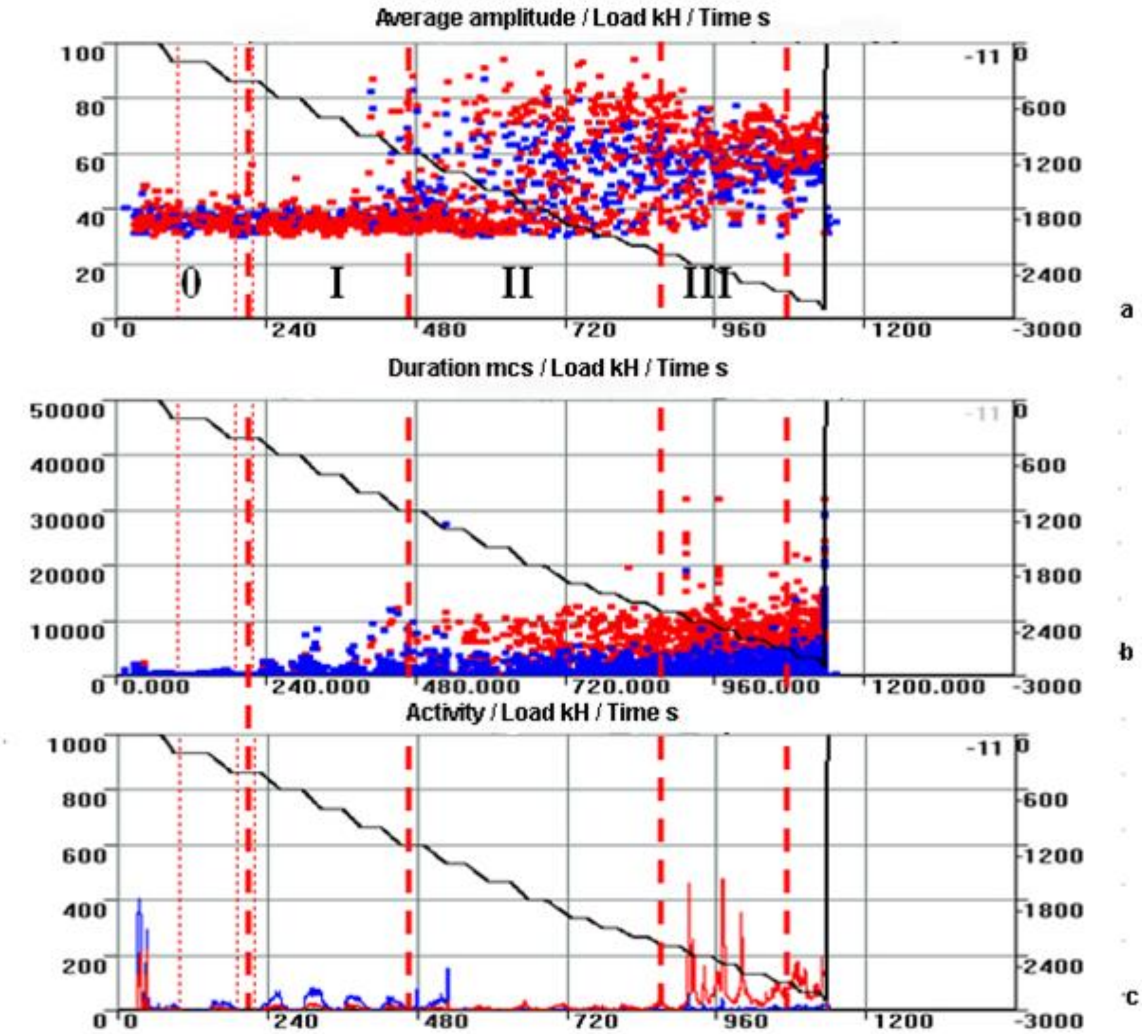

Fig. 4 Values of standard AE parameters recorded during specimen stretching -(a) time dependence of average amplitude, (b) time dependence of duration, (c) time dependence of AE activity, with superimposed load curve

Fig. 3 shows the loading diagram, involving execution of four stages when the level of tensile stress increases up to 20, 60, 90 and 120 kN. Duration of force delays at constant load was determined by activity of AE signals recording – till termination of generation of AE impulses. At the last stage the load was increased until the specimen lost its bearing capacity.

Fig. 4 shows the results of AE testing of the PCM specimen which were recorded during specimen testing – the time dependences of average amplitude, duration and activity. On this basis, one can determine three characteristic time regions: I - from 130 to 410 seconds, II - from 410 to 530 seconds, III - from 530 to 600 seconds. At the initial stage of loading the AE signals duration is not longer than 5,500 mcs (Fig. 4b, region I), in this case the average amplitude (Fig. 4a, region II) of such signals varies from 40 to 70 dB. This process according to the models discussed earlier can be assigned to the process of brittle destruction of matrix. With further increase in the load there is an increment of AE activity from 100 to 350 impulses per second (Fig. 4b, region II). Also in the region of load increase up to 123 kN an occurrence of rising trend of the time dependence of amplitude average values (Fig. 4b, area II) is observed. This process according to the previously discussed models can be assigned to the process of adhesion layer destruction. At the final stage, there is an increase in all the above parameters - average amplitude (Fig.4a), duration (Fig.4b) and activity (Fig.4c). This process can be assigned to the process of fiber destruction.

Fig. 5 Specimen of PCM installed between units of compression machine

The second stage of research is study of the AE signal parameters when the PCM specimen is exposed to compressive load (Fig. 5). Fig. 5 shows the specimen brought to failure by compressive load. The system A-Line 32D was also used as the data recording equipment. In the experiment the same transducers and preamplifiers were used as in stretching composite specimens. Tests were performed according to a loading diagram (Fig. 6) which included regions of delay and increase of the compression force level. Fig. 7 shows the results of AE testing of the PCM specimen, recorded during applying compressive load

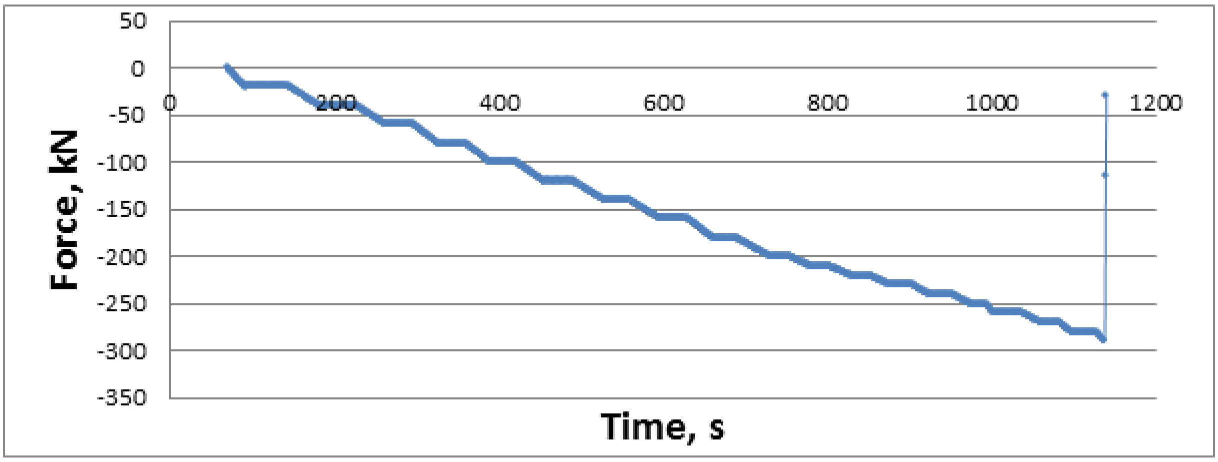

Fig. 6 Loading diagram of PCM specimen

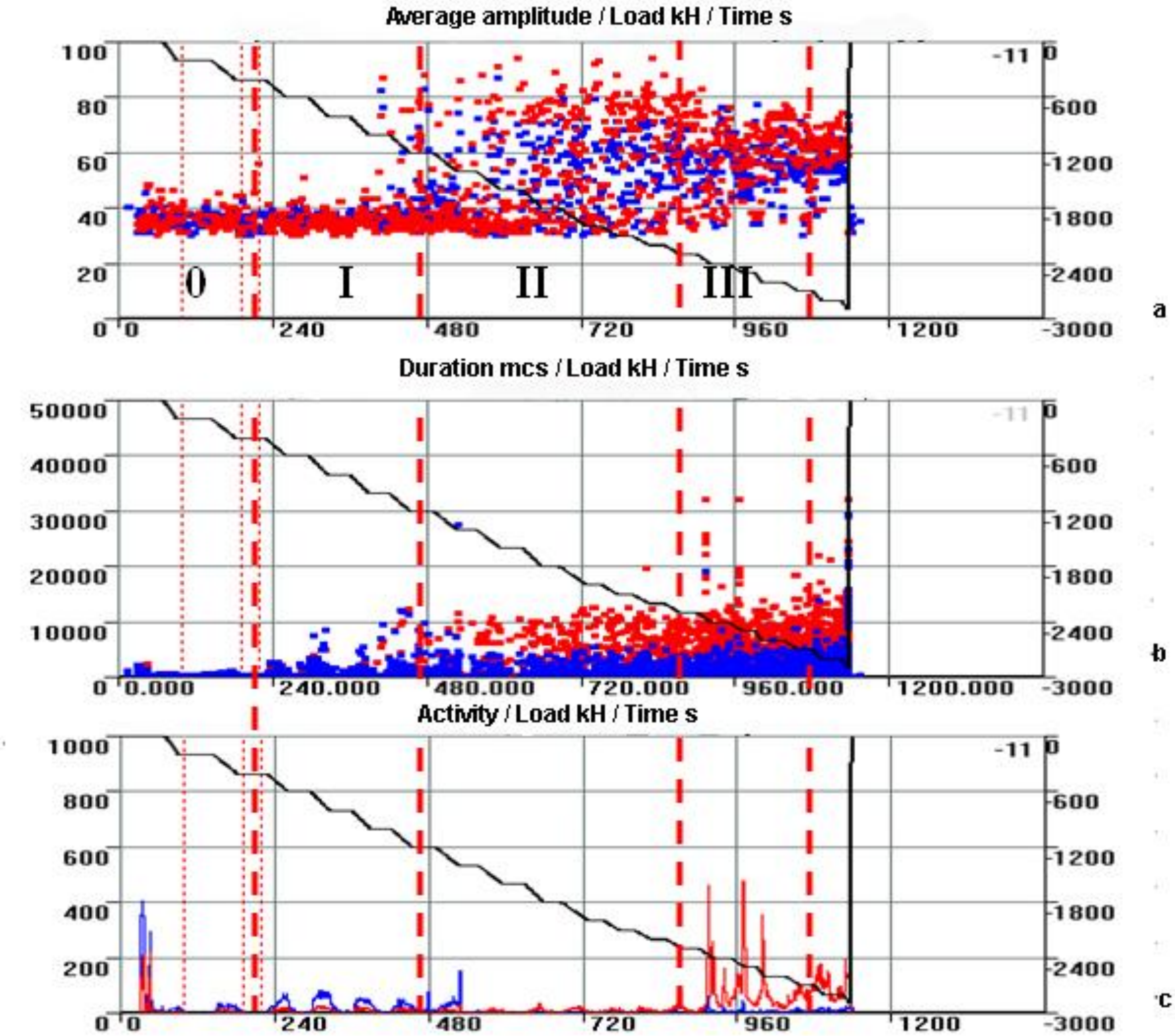

Fig. 7 Values of standard AE parameters recorded during specimen stretching – (a) time dependence of average amplitude, (b) time dependence of duration, (c) time dependence of AE activity, with superimposed load curve

Fig. 7 shows the time dependences of standard AE parameters. On this basis one can determine three characteristic time intervals: stage 0 – from 0 to 84 seconds, stage I - from 84 to 392 seconds, stage II - from 392 to 916 seconds and stage III - from 916 to 1,138 seconds. The stage 0 corresponds to pre-loading of the object under test, which is loading by small action wherein alignment of grips and the specimen is checked. At the initial stage - from 20 to 120 kN - acoustic signals of short duration are recorded (Fig. 7b, region I.), in so doing, the amplitude average value does not exceed 50 dB (Fig. 7c, region I). According to the models accepted, such parameters of AE data correspond to the process of matrix destruction. Further increase in the load leads to the AE activity increase from 50 to 180 signals per second (Fig. 7c, region II.), and also there is an increment of values both of the average amplitude parameter - up to 90 dB, and of the duration parameter - up to 20,000 mcs. Such process can be associated with the adhesion layer destruction. At the final stage there is an increment of all above parameters – average amplitude (Fig. 7a, region III.), duration (Fig. 7b, region III.) and activity (Fig. 7b, region III.), that may be typical for the fiber destruction. As a result of experimental AE data analysis the key stages of composite material destruction were identified [1,2].

Data Analysis

During data processing two typical forms of AE signals were determined (Figs. 8 a,b). The first type signals (Fig. 8a) were recorded from the beginning of internal pressure buildup and to complete destruction of the object. By the standard parameters values and by the form, the first type signals correspond to the process of matrix destruction. The second type signals (Fig.8b) were recorded at the later stages of destruction. By the standard parameters values and by the form, such signals belong to the process of fibers destruction.

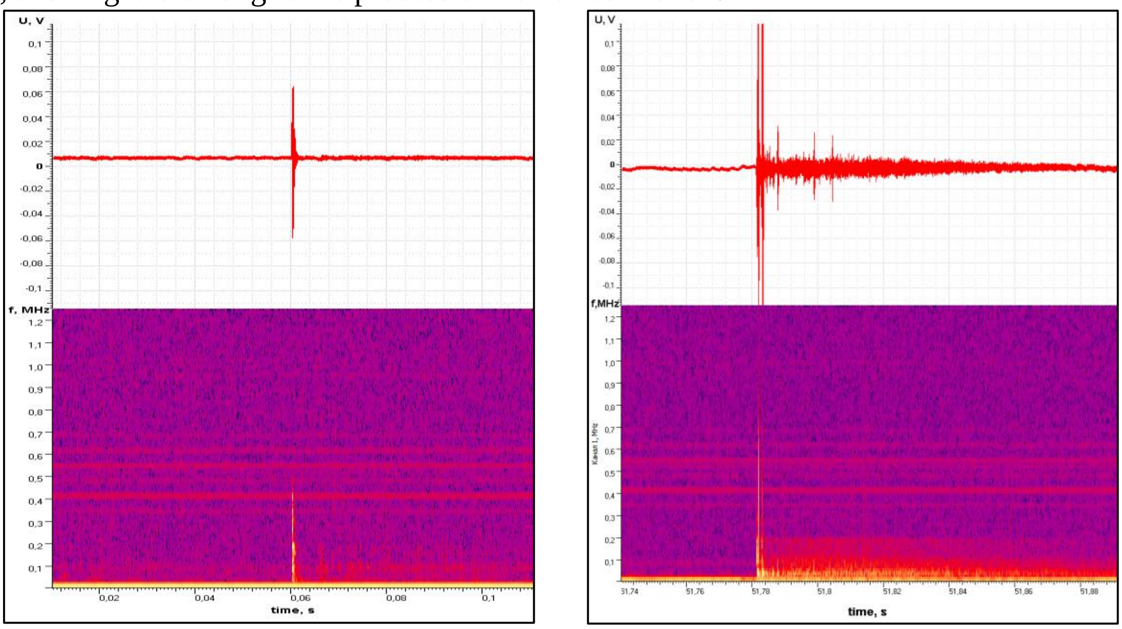

Fig. 8 Form and spectrogram of AE signal corresponding a. to matrix destruction b. to fiber destruction

Both types of signals can be described by invariants of form. The first invariant of form (4) is the ratio of decay time t_{decay} to rise time t_{rise}. On its basis, it is possible to detect acoustic signals of long duration, which correspond to the process of delamination and destruction of fibers.

$$Criteria_1 = t_{decay}/t_{rise} \tag{4}$$

$$Criteria_2 = A \cdot t_{decay} \quad (5)$$

The second invariant of form (5) is a product of the AE signal amplitude A and the value of decay time t_{decay}. These parameters can be used for filtering noise signals and selecting AE pulses with a sharp front and a short duration, which belong to the process of matrix brittle destruction.

AE diagnostics of high-pressure metal composite vessel

To evaluate the efficiency of developed criterial estimations, they were put to an evaluation test during the object testing to destruction [5, 8]. As the object under test, the metal composite vessel was used which composed of titanium liner and composite shell (Fig. 9), brought to destruction through stepwise increment of load (Fig. 10).

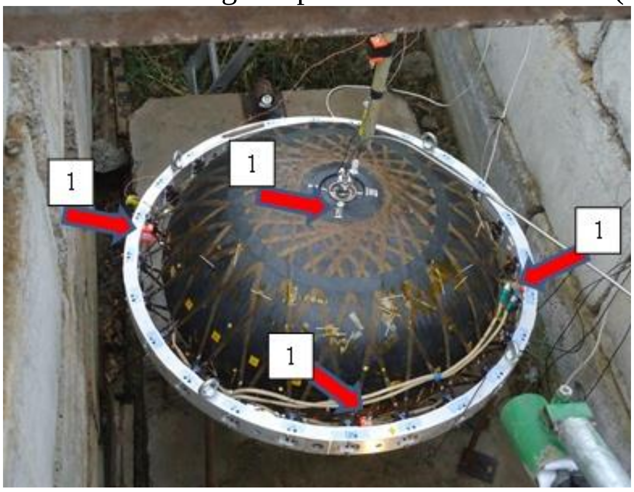

Fig. 9 Metal composite vessel located in protective bunker 1 – points of TAEs installation

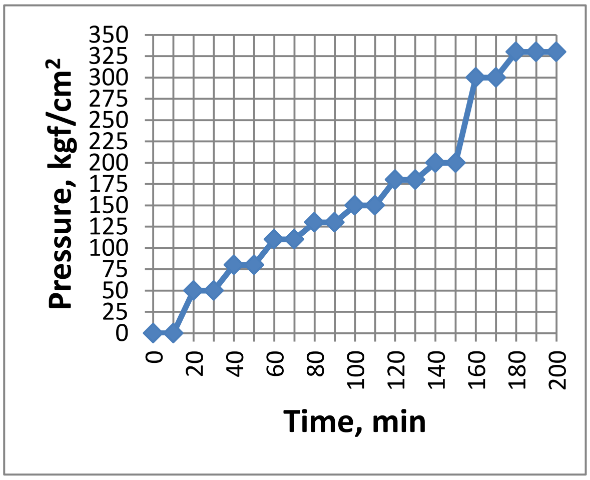

Fig. 10 Loading diagram of object under test

Fig. 10 shows the loading diagram consisting of sections of pressure buildup and delays, base values of which correspond to 50, 80, 110, 130, 150, 180, 200, 300 kgf/cm^2. Further pressure buildup resulted in the object complete destruction (330 kgf/cm^2).

During the tests, the AE data were recorded both by the industrial system A-Line32D and by the continuous recording unit L-Card**.** In the experiment AE sensors GT200 were used having resonance frequency of 165 kHz, as well as preamplifiers of the company LLC "INTERUNIS" characterized by a bandpass of 25-500 kHz and gain of 26 dB.

Processing of AE data obtained during tests

Destruction of the object under test consists of two stages – deformation of titanium liner and destruction of composite shell. Titanium liner strain begins at the load of 1 kgf/cm^2 and continues till vessel destruction. Titanium would be fully subject to plastic strain when pressure value is 30 kgf/cm^2. Once pressure value reaches 30 kgf/cm^2 strain intensity decreases, as titanium turns into plastic mass. The composite material destruction starts at pressure value about 50 kgf/cm^2.

The first stage of research is matching of the stages of metal composite vessel destruction with AE data. The main goal of study is identification of characteristic dependences corresponding to the destruction stages determined earlier.

At the initial stage of pressure buildup there is an intensive straining of titanium liner. The process of active strain in the form of reduction in the shell thickness occurs in the area of poles, from pole to equator the material elongates with the cross-section loss. The process of liner plastic strain is characterized by continuous emission, which is an additional difficulty in data interpretation (Fig. 11). The main difference of such signal from noise flux is a spectrogram form, which allows for revealing the plastic strain against the background noise.

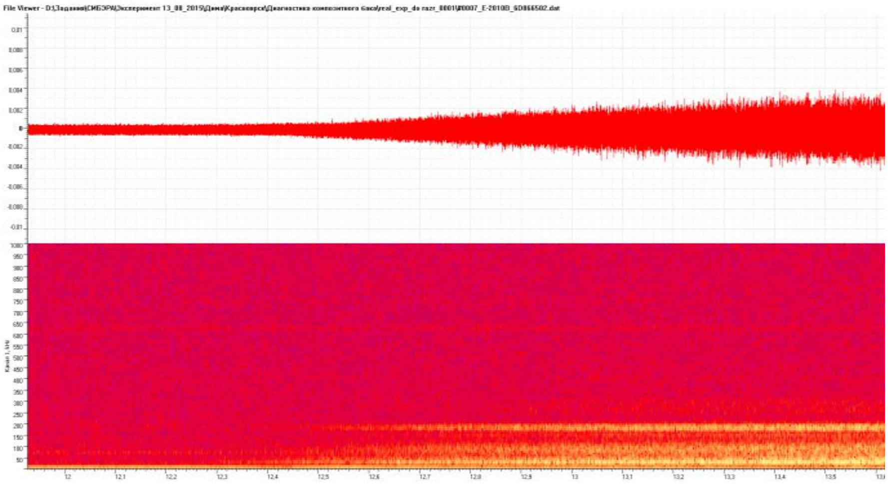

Fig. 11 Oscillogram of liner plastic strain process

With further increase in load the beginning of composite shell straining is observed. The composite straining begins with the processes of matrix cracking and delamination. These processes are characterized by specific trend of amplitudes growth (Fig. 12).

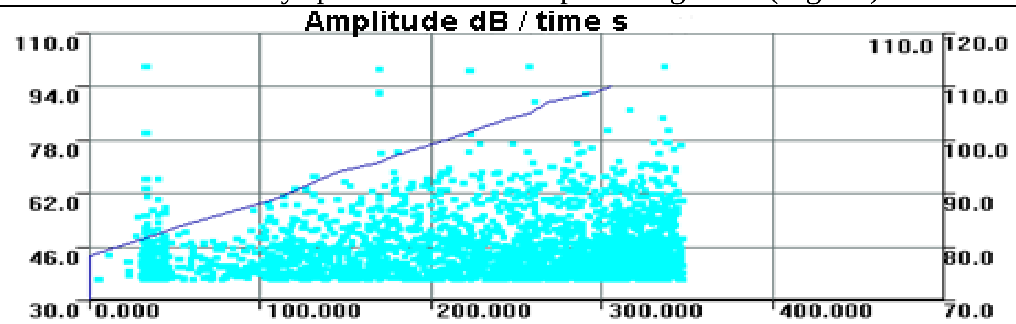

Fig. 12 Time dependence of AE-pulse amplitude under loading up to 110 kgf/cm^2 with the superimposed load curve

Fig. 12 shows the amplitude dependence with a characteristic increasing trend. The increasing amplitude trend characterizes the process of damage accumulation in the composite material matrix, as well as the transition to the next stage of object deformation.

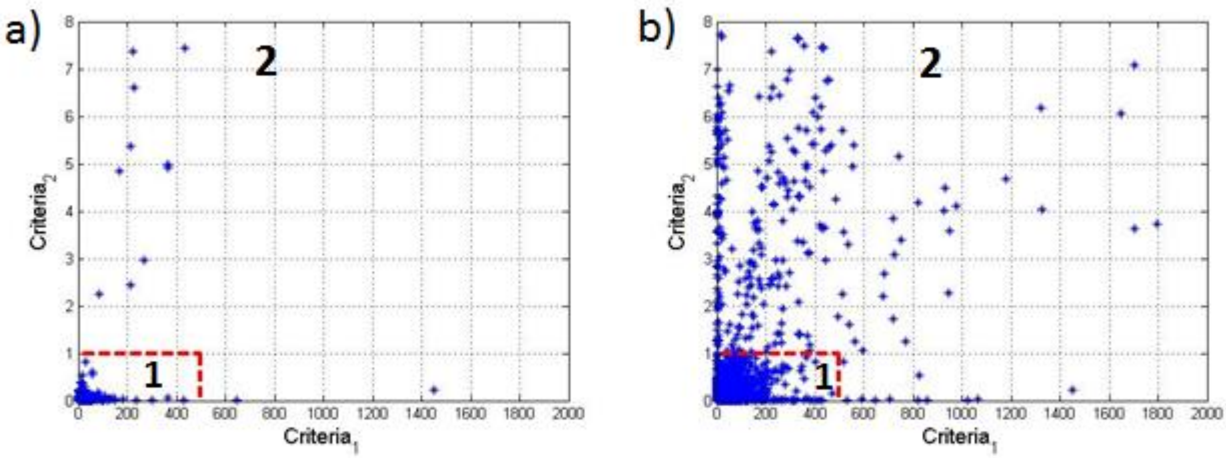

Fig. 13 Separation of signals by two types using the developed criteria (a) criterial plane when loaded to 120 kgf/cm^2, (b) criterion plane when loaded to destruction

Drawing of a criterion plane on the basis of invariants of acoustic waveform will also permit to separate the stages of composite material destruction. And on the activity calculation of each of signal types it is possible to assess the intensity of damage accumulation.

Fig. 13 shows the result of AE signals separation by two types at different load levels. Under loading to 120 kgf/cm^2 (Fig. 13a), the point density raises only in the first cluster that includes AE signals occurring during the matrix destruction. With further increase in load (Fig. 13b) the activity of acoustic signals increases in the second cluster, which can be assigned to the process of fibers destruction.

To evaluate the intensity of damage accumulation, the activity assessment algorithm was used for each of determined types of AE pulses. The algorithm is an approximation of total account of the specific type signals (Fig. 14).

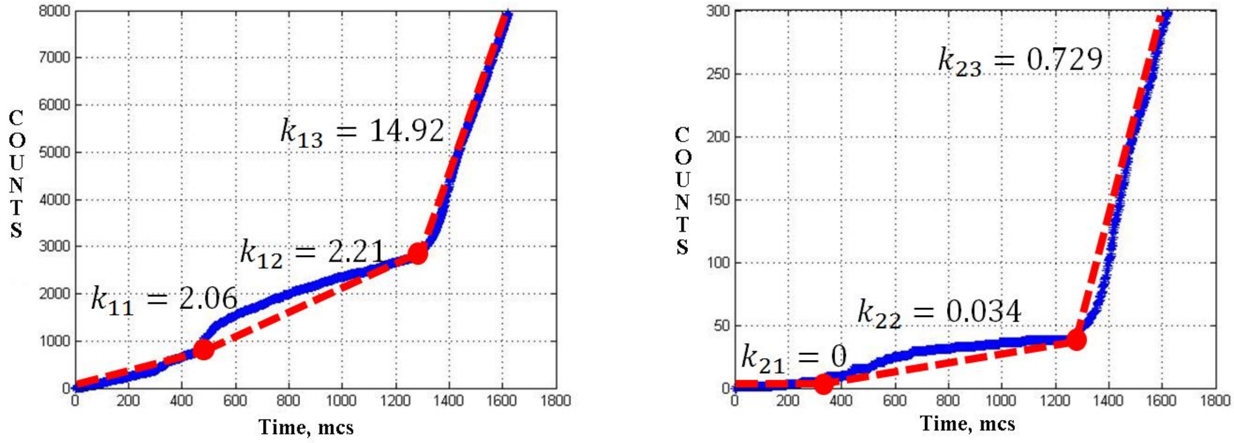

Fig. 14 Approximation of total account function - (a) the first type signals, (b) the second type signals

Fig. 14 shows the total account functions of signals of the first (Fig. 14a) and second (Fig. 14b) type. For the numerical evaluation of damage accumulation intensity the calculation of k-factor was performed after piecewise-linear approximation by function $y = kx + b$. The higher the k-factor value, the higher the damage accumulation intensity. Thus, within the framework of assigned task it has been possible using the developed criteria to separate the stages of metal composite object destruction, as well as to evaluate the damage accumulation intensity.

Conclusion

As part of the study a large amount of work was carried out. Initially the main stages of composite material destruction which occur at different types of loading were studied. To solve the problem of evaluating states of composites and matching the destruction stages and the AE signal parameters, laboratory tests were carried out, which included destruction of specimens using compressive and tensile loads. Upon experiments performance, the most informative parameters of AE signal were determined, on the basis of which the criteria parameters were developed. Criteria for evaluating the composite destruction stage, as well as the intensity of damage accumulation were developed.

To check the efficiency of developed method, destructive tests of metal composite vessel were performed. Application of the developed criteria also allowed for separating the stages of object destruction.

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