638. Acoustic emission and methods of its registration (review)

[1]Bogorosh A. T., [1]Voronov S. A., [2]Royzman V. P., [3]Bubulis A.
[1]National Technical University of Ukraine (Kiev Polytechnic Institute)
[2]Khmel'nitskiy National University, Ukraine
E-mail: *roizman@mailhub.tup.km.ua*
[3]Kaunas University of Technology, Lithuania
E-mail: *algimantas.bubulis@ktu.lt*

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Abstract. Lately a tendency is observed for the steady growth of requirements applied both to construction materials as well as to the methods of estimation of their reliability and quality. Particular attention is paid to the development of new, physically reasonable criteria of structural durability of materials, based on comprehensive study of the phenomena, which form the basis of processes of deformation and fracture. Such approach is supposed to enhance our understanding of the nature of durability and mechanisms of fracture of materials on different scale levels. This is possible only when analysis of these phenomena is accomplished by means of modern physical research methods as well as applying acoustic emission techniques for diagnostics of the fractures.

Keywords: acoustic emission, non-destructive testing, structural health monitoring.

Introduction

As practice indicates the solution of a considered complex problem of bearing capacity of materials and constructions is possibly on at the intersection of materials science, physics and fracture mechanics, i.e. in new schools of micromechanics of synthesis and destruction as well as physical mesomechanics [2,3]. The methods of classic materials science are not excluded as well. Wide prospects are foreseen for novel approaches which combine the principles of synergy and the theory of fractals, including the durability and fracture of materials assessed by means of acoustic-emission methods of diagnostics and information reception [4-6].

It is known that a method of acoustic emission (AE) based on registration and processing of waves of strains which arise as a result of deformation, modification and destruction of structures is presently the most effective for the study of processes of development of defects and creation of the systems of the continuous structural health monitoring of important industrial objects.

The first works on the study of the AE phenomenon appeared at the end of 40s of the 20th century in the USA and at the beginning of 50s in Germany. The development of electronics and creation of the special analog AE devices at the end of 60s allowed application of AE method for the detection of growth of thickness of deposits on heat-transmitting surfaces and cracks in the process of different mechanical tests. Review of these works, including authors, is provided in [7-9].

The analysis of current publications on the subject matter indicates that the whole problem related to the AE method can be presented by the following scientific directions [10]:

- Theory and methods of diagnostics and prognosis of bearing capacity of constructions including issues related to theoretical and experimental studies of destruction.

- Information-measuring systems intended for the analysis of AE information necessary for making decision about the state of constructions.

- Mathematical support of measuring apparatus including the executable programs of organization of input information processing and subprograms related to the compression of information, increase of authenticity of measuring results based on the theory of recognition of patterns, mathematical statistics and theory of chances.
- Theory of prognostication and decision making.

A special place is occupied by the use of AE method for the study of processes of accumulation of damages in loaded materials for non-destructive control and evaluation of bearing capacity of materials and wares.

The existing control methods are based on the analysis of parameters of AE signals. The methods of processing of signals and definition of their informative parameters depend greatly on the type of registered AE. It is accepted to distinguish discrete and continuous AE. To understand the choice of informative parameters during registration of one or another type of AE we will examine the basic terms of formation of acoustic signals in solids.

Because of the discrete nature of matter, the physical processes are discrete as well. Seemingly continuous process reflects the fact of averaging the result of supervision of large number of separate elementary events. Elementary event in a solid results in its deformation, but so insignificant, that it, as a rule, cannot be registered by the known means. But plenty of elementary events, formative the sequence (stream) of events, can result in the macroscopic phenomena that produce the noticeable change of the energetic state of body. During the release of energy part of it radiates as elastic waves. Generation of such waves is referred to as acoustic emission.

AE can be manifested in two ways. If the number of elementary events resulting in the origin of elastic waves is large and energy released at every event is small then AE signals are perceived as weak continuous noise named **continuous** AE. Because of smallness of energy released at a single act the energy state of a body changes insignificantly. Probability of occurrence of next such act practically does not depend on the previous one. As a result, descriptions of continuous AE variations in time comparatively slowly that allows to consider this type of emission as a quasi-stationary process.

If the state of body is far from equilibrium then processes of avalanche type are possible, when for the small time interval a large number of elementary events are engaged in a process. Energy of elastic wave here can by many orders of magnitude exceed the energy of elastic waves at continuous emission. Similar emission characterized by large amplitude of the registered acoustic impulses was termed **discrete.**

It should be noted that dividing of AE into continuous and discrete is rather arbitrary since the possibility of separate registration of the AE pulses depends only on the characteristics of the equipment used.

In the real-life situation, as a rule, we have to deal with emission of both types of acoustic emissions. The creep of material on the first, non-stationary, and second, stationary, stages is accompanied by continuous AE. On the third stage, besides continuous, discrete AE conditioned by formation and development of microcracks is also observed. The same occurs during corrosion under tension, the final stage of which – corrosive cracking – is accompanied by the intensive acoustic flashes of discrete AE. For prediction of destruction it is common to make use of discrete AE component due to simplicity of registration of signals characterized by large amplitude.

Discrete AE is also applied for control of technological processes [6], when the formation of cracks is possible (welding, tempering, diffusive saturation, for example hydrogenation and other) as well as for research and control of the corrosive cracking, durability, heat durability, fatigue destruction, and also processes of friction and wear. Continuous AE is connected with plastic deformation, corrosion of materials and other physical processes.

It is necessary to distinguish the informative parameters of separate impulses of discrete AE, streams of impulses and parameters of continuous AE. Impulses or signals of AE are characterized by amplitude, duration, form and time of occurrence. The stream of signals additionally can be characterized by average frequency of events, spectral closeness, amplitude, temporal and peak-temporal distributions, cross-correlation function, mean value and dispersion. Each characteristic is related to AE generating physical process and contains information about its development or about the state of the research object.

For discrete AE the following informative parameters are introduced:

1. The total number of impulses N_Σ is a number of the registered impulses of discrete AE for an interval of observation time. The very determination of this parameter suggests its suitability for description of streams of the non-overlapping impulses only.

2. Activity of AE is the total number of impulses per time unit. Informatively this parameter is the same as previous. This makes it possible to observe the dynamics of process of destruction.

3. Total AE is a number of the registered emissions of AE – of signals of the defined level during the set time interval. Thus response ratio of its reproduction in a counting device depends on the level of discrimination, coefficient of attenuation of oscillations in an object and transformer, and also on the descriptions of receiving-amplifying section.

4. Counting speed $\dot{N}$ is a number of registered AE emissions – of signals of the defined level per time unit. Some authors call this parameter "the intensity of AE".

5. The probability density of amplitude of impulses $w(A)$ characterizes AE as a random process. This function determines the probability of AE-impulse A_0 amplitude presence in an interval from A to $A+dA$:

$$P\{A < A_0 < A+dA\} = w(A)dA \tag{1}$$

In practice, characteristic $n(A)$, amplitude impulse distribution is used more frequently. This function specifies the amount of impulses, amplitude of which is within a small interval from A to $A+dA$. If N is the total number of the registered impulses, then amplitude distribution is related to the probability density $w(A)$ as:

$$n(A) = N \times w(A) \tag{2}$$

$$N = \int_0^\infty n(A)dA \tag{3}$$

Functions $w(A)$ and $n(A)$ can be estimated from experimental data by forming the histogram of distribution of AE impulses with respect to amplitude. It is generally known that this histogram reflects the amount of impulses n_i dependence (or parts of such impulses n_i / N) amplitude of which is within a small interval from A_i to $A_i + \Delta A$ on the size of amplitude A_i. It is easy to determine the correlation between these functions:

$$Nw(A_i)\Delta A = n(A_i)\Delta A = n_i \tag{4}$$

Defining from experimental data with the use of these correlations the set of values of functions $w(A_i)$ and $n(A_i)$, in future, for example using the system of distributions of Pearson, it is possible to pick up analytical formulas for description of functions $w(A)$ and $n(A)$.

6. Time intervals distribution $W(\tau)$ between separate AE-impulses contains important information about the physics of the phenomenon and nature of its development. At mutual independence and identical probability of elementary events their sequence (stream of events) is described by the law of Poisson. If a stream is stationary, then distribution of the time intervals between the impulses of AE is described by the exponential law:

$$W(\tau) = \nu \exp(-\nu\tau) \quad (5)$$

The mean value of temporal interval between impulses equals $\tau_0 = 1/\nu$. And in contrast – if intervals between separate events have exponential distribution, then events are described by Poisson law. Such conclusion gives evidence of separate events interconnection absence that by itself is important information about the nature of the process, for example about the delocalized destruction of construction material.

7. Amplitude-temporal distribution of impulses of AE $n(A;t)$ is a function that indicates the amount of impulses of AE dN, registered within the interval of time from t to $t+dt$, amplitude of which is within an interval from A to $A+dA$:

$$dN = n(A,t)dAdt \quad (6)$$

If we will integrate this function over time from 0 to T - time of the registration of AE, then we will determine distribution of amplitude of the AE impulses and if we will integrate once again over amplitude, then we will obtain the total number of impulses over the registration time:

$$n(A) = \int_0^T n(A,t)dt \quad (7)$$

$$N = \int_0^\infty \int_0^T n(A,t)dtdA \quad (8)$$

In other words, amplitude-temporal distribution reflects temporal variations of distribution of amplitude of the AE impulses.

8. Spectral density $S(w)$ **of discrete AE** matches corresponding characteristic of random process and is equal to power of process in the single frequency band.

Informative content of this characteristic is the same as that of the spectral density because they are connected by direct and inverse Fourier transform. In addition, the unidimensional and multidimensional distribution functions of the parameters indicated earlier are implemented.

Methods of selection of AE signals in noise

Research of the AE phenomena conducted under various conditions on different materials indicates that the signals of AE have a wide spectrum of amplitude-temporal parameters. The signal of AE can be registered on any frequency, but amplitude of the registered signal decreases in inverse proportion to the frequency. For this reason, it seems obvious to seek for AE signal reparations at low frequencies. Furthermore, the attenuation of elastic waves increases significantly with increasing frequency. However, decrease in frequency leads to increase in acoustic noise of AE signals transformer and of electronic equipment.

Passive methods of dealing with noise and interference are used in virtually all devices and systems of AE signals recording and processing.

Amplitude discrimination, as noted above, is one of the blocks in the analogy section of AE systems and serves to cut off the noise on the basis of the amplitude by comparing incoming signals with some preset value.

In addition to a fixed threshold limit sometimes a floating threshold is used, i.e. continuous monitoring of the change in the level of interference in the channels of the AE signal section gain.

Frequency filtration is also realized by one of blocks in an analogy section and consists in limitation of amplifying channel bandwidth. Limitation in low frequency area lies within the limits of 20..200 kHz, and in high frequency area - 1,5..2 MHz. Limitation in the low frequency area is due to the necessity of noise cut-off of mechanical and testing equipment, and limitation of the frequency range from above - by the necessity of the electromagnetic noise cut-off. Sometimes frequency filtration is used for a selection of narrow bandwidth, determined by the testing conditions for a specific material, longitudinal and transversal wave speeds of distribution in it, and also for registration of cracks with certain sizes.

A temporal selection consists in AE signals registration channels locking during the interference. As a disturbance indicator, typically electromagnetic, serves a special channel that registers only the noise.

A parametric selection or parametric gating consists in passing the AE signal for processing to the electronic system only under certain loading conditions, for example, when the load of a certain reassigned level is achieved. This type of selection is usually used during fatigue tests.

A spatial selection is used to identify whether accepted signal is the AE signal or interference by determining the spatial location of signal source. Such systems require the use of multichannel systems. The minimum number of channels during operations with linear objects is equal to two.

A two-parameter selection is usually used in the analogy-digital AE systems and consists in signals rejection with specific values of their parameters. So, for example, signals with large amplitude and short duration correspond to the electromagnetic interference and signals with a relatively small amplitude but long duration are typical for the mechanical noise. Such distinctions allow distinguishing the real AE signals which have these parameters in intermediate range from mechanical and electromagnetic background interference.

In the analogy-digital AE systems it is possible to use a direct interfering signals deduction from the totality of registered AE signals. For this purpose the preliminary record of interference signals is performed in loading equipment in specific working conditions and for other types of interference.

Sources of acoustic emission in materials

At the present stage of AE research and development the following basic AE sources operating on different structural levels in materials could be distinguished:

The mechanisms responsible for a plastic deformation: processes related to motion of dislocations (conservative sliding and dislocations annihilation, dislocations reproduction by the mechanism of Frank-Read; separation of dislocation loops from the pinning points, etc.); grain boundary sliding; twinning.

Mechanisms related to phase transformations and phase transitions of the first and second order: polymorphic type transformations, including martensite; second phase particles formation during the decay of supersaturated solid solutions; phase transitions in magnetics and superconductors; magneto-mechanical effects due to borders displacement and magnetic domains reorientation during the change of external magnetization field.

Mechanisms related to destruction: micro-damage formation and accumulation; crack formation and development; corrosive destruction, including corrosive cracking.

Table 1 presents data that provides an idea about the characteristics of some of these AE sources.

Special literature contains data on the level of acoustic noise caused by the thermal motion of atoms.

In polycrystalline materials generation of continuous AE is usually associated with the plastic deformation of polycrystal individual grains. In the polycrystalline structure due to uneven stress distribution plastic deformation of separate crystals occurs at low total strain when the metal is in the area of elasticity from the phenomenological point of view. Therefore through AE signals it is possible to judge about the formation of irregularities and micro-defects in the initial stage of deformation and fracture of materials.

The practical use of the AE phenomenon is based on elastic energy registration released in the controlled object material. Defect origin, movement and growth are accompanied by the change of microstructure and stress-strain state of the material. Thus redistribution of elastic energy happens that results in emission of AE signals. Discrete AE occurs during the development of defects [8]. Therefore, it can help to identify the initiating defects that are potentially dangerous in terms of catastrophic failure. This AE method compares favorably with the traditional methods of ultrasonic testing. Therefore, most of the experimental and theoretical works in AE area are devoted to the study of the relationship between AE signal characteristics and material stress state and fracture parameters. Many authors have attempted to define the functional or correlated connections between crack parameters and registered AE signals without dwelling on the preconditions that allow such relationship dependences (in some cases, they are determined from the results of data processing).

Table 1. The AE signal parameters for some sources

AE source type	Amplitude or AE impulse energy, Pa or J	Signal duration, μs	Signal spectrum width, MHz
Frank-Read dislocation source	$((10^{-8}$- $10^{-7})$ G; G is the shift absolute value	$5^{-5}\times10^{4}$	1
The annihilation of 10^{-8}-10^{-6}m long dislocation	$4\times(10^{-18}$- $10^{-16})$	5×10^{-5}	10^{2}
Micro cracks formation	10^{-12}- 10^{-10}	10^{-3}- 10^{-2}	50
The disappearance of 10^{-9}m^{3}-sized twin	10^{-3}- 10^{-2}	10^{4}	-
Plastic deformation of material with a characteristic size of 10^{-4}m	10^{-4}	10^{3}	0,5
Thermal noises energy in the single frequency band	$4{,}2\times10^{-21}$J/Hz	-	up to 10

From the dependences presented above, according to most researchers, the most reliably established and sustained is an exponential connection between the total count of AE impulses and stress intensity factors at the vertex of a growing crack. The exponent *m* is associated with the sizes of plastic deformation area in vertex of a developing crack. However, if you stick to this point of view, then the value of parameter *m* should be equal to four. Experiments provide a wider range of variation of this parameter. It is determined that the exponent *m* is a function of dimensionless complex K_{Ic}^{2}/E_{n}, including fracture toughness K_{Ic}, Young's modulus *E* and surface energy *n* of the material. Depending on the complex magnitude of the parameter *m* for different materials can vary in the range from 4 to 10,5, which well agrees with the experimentally observed values of this index.

We should also mention publication [12], which reports the results of careful experimental studies and demonstrates that the sum of the peak amplitudes of AE pulses is associated with the area of cracks in brittle fracture of materials in a linear relationship.

In recent years research works were performed in the area related to AE in heterostructures, the results of which were provided in the review article [25]. However list of references [12-24] was shortened by editorial staff of the journal without the consent of the authors in the process of translation into English, for that the editors would like to apologize to authors of these works.

Conclusions

Physical basis and scope of the acoustic emission (AE) registration method have been examined in the presented review paper. The advantages of this method are as follows:

- Efforts associated with preparatory procedures and the monitoring complexity is by tens (hundreds) times smaller than in the case of other methods of nondestructive testing (NDT): this method does not require surface continuous scanning, i.e. allows to set sensors on the investigated object locally (surface area for AE sensor placing is from 1 mm^2 to 150 cm^2), which considerably reduces production costs: isolation minimal removal, surface minimal stripping).

- It is global in volume control. Control of the whole object with determination of the defect origin and development locations (location mode) is realized by installing several sensors. This allows using this method for control of inaccessible surfaces and also to carry out continuous condition monitoring of the object during functioning and go from periodic technical examinations to exploitation of object on his actual technical condition.

- It allows diagnosing an object as a whole, without taking it out from the existing mode of exploitation or taking it out for a minimum time that gives obvious economic advantages as compared to the traditional NDT methods that require termination of facility operation to conduct monitoring.

- AE control method provides the detection and registration of initiating, and, therefore, highly harmful defects, and performs their classification not by size, but by the degree of negative impact. It means, in particular, that some, for example round defects the size of which exceeds the acceptance level of traditional NDT methods, using AE control may fall into a class of non-hazardous, since they exist but do not develop during the operation of an object. It allows us to reasonably cancel the stop of the object and repairs which in a number of cases only reduce reliability of an object.

- It is characterized by the versatility with respect to the choice of the diagnosed object, i.e. it can be used without limitations for evaluation of any object where the change of pressure (load) for initiation of possible defects can be provided.

- It has a high efficiency: the time spent on preparatory works and technical diagnosis is much lower compared to the traditional NDT methods.

The disadvantages affecting the measurement accuracy may include features such as:

- necessity of acoustic contact of transformer with the control object;
- increased requirements to the purity of the product surface;
- eternal noise influence on the measurement results;
- influence of object temperature and vibration, etc.

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