ACOUSTIC EMISSION OF DIAGNOSING OF BRITTLE FRACTURE IN STRUCTURAL MATERIALS

Valentyn SKALSKY, Oleg SERGIENKO, Roman PLAKHTIY
KARPENCO PHYSICO-MECHANICAL INSTITUTE OF NATIONAL ACADEMY OF SCIENCES OF UKRAINE
Lviv, Ukraine

Introduction. Long term service of various equipment, machines and responsible constructions results in degradation of structural materials of which they are made. Degradation is accompanied by embrittlement that assists formation and development of cracks that are the most dangerous for structural strength defects. In the case of brittle fracture cracks could cause spontaneous failure, which, mostly, results in substantial financial losses, violations of ecological situation, human victims etc.

According to conception of “safe damage” a presence of cracks can not always be the reason for replacement of a product or its element. To provide their regular functioning one can be able to distinguish critical parameters of cracks, which characterize the stages of crack propagation, namely, its start, subcritical growth and transition of fracture mode to the overcritical stage.

The expedience of application of acoustic emission (AE) diagnostics for materials and structure elements has long been confirmed [1-4], however to this day there is a problem of development of more effective methods and facilities for their realization in evaluation of brittle fracture in structural materials that is based on the stable parameters of AE signals (AES). Solving of this actual scientific and technical problem will allow identifying the stages of critical fracture of materials, diagnosing the state of structural elements, and even evaluating their residual life more effectively applying AE monitoring.

Development of digital signal processing of AE data in 70th of XX century allowed applying spectrum analysis of AES for determination of fracture mechanisms in solids. Together with the waveforms of AE event, amplitude-frequency response of AES enables to estimate the features of AE source by investigating AES fine structure. However, for the estimation of AES spectrum it is necessary to utilize broadband transducers of AE waves into electric signals along with other proper facilities. In practice this problem is rather complicated. As a rule, serial piezoelectric transducers are most often used in AE testing. The have limiting working frequency band because of their construction features. From the other hand, in AE testing of structure or their elements we have to select for determination of fracture types such parameters of AES, which have high stability regardless of specificity of elastic wave propagation in the tested component, modes of selection and processing of AES, type of AE transducer etc. It will allow not only to promote quality of diagnostic works, but also effectively distinct the stages of subcritical crack growth.

Thus, the main goal of our investigation is to develop the methods and facilities for diagnostic of brittle fracture of solids under quasi-static mechanical loading by the evaluation the changes in the most stable parameters of AES.

Development of model and criterion for estimation of fracture types in solids. In the researches known from literature one or two parameters of signals of AES are used. They are recorded often even without taking into account the sensitivity of AE transducers, their working frequency band etc. Therefore, using these qualitative parameters of known methods, determination of fracture type is impossible. This fact induced us to develop effective methods of quantitative estimation of fracture types, considering few most stable parameters of AES, transfer characteristics of transducer as well as the peculiarities of AES passing in the analog highway of AE device.

In monographs [3, 6, 7] it is noted that important information about the stages of subcritical development of crack can give the analysis of spectrums of AES. Their analysis allowed to formulate the criteria for estimation of the state of structural elements or products, which have crack-like defects [6, 7].

Theoretical researches of AES structure (including signal spectrum) have shown that narrowing of frequency band of AES with a crack growth depends on stress intensity factor (SIF)

[1]. Calculations have shown that depending on the crack size the frequency band can rich a few megahertz. However, the proper operation of AE devices in a megahertz range is complicated due to technical reasons. Experimental researches give evidence that informative frequency range for crack inspection is from 0,1 to 4 Mhz [7]. Taking into account different technological factors, noise, design features of transducers, usually the spectrum of AES lies in the range to 1 MHz, and peak maximum of frequency spectrum corresponds to the frequency of less than 400 kHц. In this case the results of tests insignificantly depend on material, AE transducer, sizes of specimens, and method of AES processing. However, it is known that the spectrum of AES not only contains information about physical processes, which generate AE but also depends on a shape and sizes of a specimen, characteristics of AE transducer. All these factors could substantially change AES emitted by the defect [8-20].

We tested structural alloys (steels, aluminium alloys, glass, concrete, etc.) in order to determine their fracture toughness using modern and our own AE devices. As a result of experiments we confirmed the specificities of spectral characteristics of AES at the different stages of subcritical crack growth.

Substantial effect on changes in parameters of elastic waves of AE in different materials has their attenuation [19]. It must be taken into account during the non-destructive testing of materials, products and structural elements. Rise time of AE signals is related to the fracture mechanisms determining its ductile or brittle type. Amplitude of AES is determined by the sizes of formed defects (or by the size of crack jump). Thus, analyzing the rise time AES, which carries information about AE event, its amplitude frequency characteristics, one can determine the fracture.

The different parameters of AE signals show different stability to the physical factors, in particular to the threshold level and propagation distance. Therefore, as the informing parameters of AE signals maximal stable parameters are to be chosen, or actions for increasing stability should be taken.

On this ground, the descriptive physical model of mechanisms and fracture stages effect on the feature of elastic AE waves as well as criterion for evaluation of brittle fracture in a solid are proposed. A model is based on the following fundamentals:

1. Most dangerous defects in solids, which result in spontaneous failure of products and structural elements, are crack-like defects.

2. Nucleation and subcritical growth of these defects have the long-term period; it is important to correctly differentiate stages of this period when diagnosing products and structural elements.

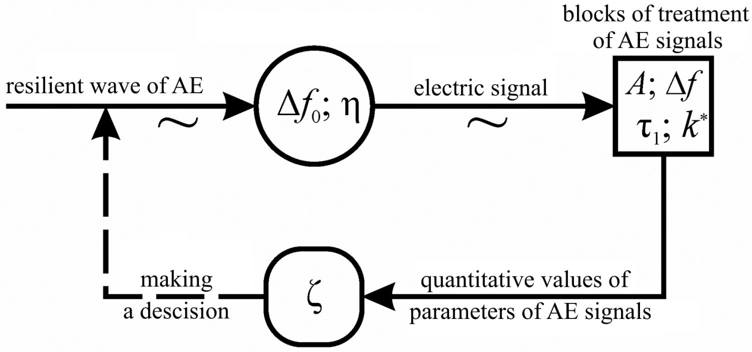
3. During nucleation and development of fracture in solids, the released energy emits partially as elastic AE waves.

4. Different mechanisms and stages of subcritical growth of crack-like defects are accompanied by inherent AE.

5. Brittle fracture of structure materials should be diagnosed using most stable AE parameters that will to estimate the residual life of products and structures with a high reliability.

6. The criterion of estimation of brittle macro-fracture by means of the electric parameters of AES should allow distinguish brittle and ductile fracture of inspected products.

For the elaboration of such criterion, we used the diagram shown in Fig. 1.



Rice. the 1 Diagram for determination of criterion parameter ζ

Taking into account the fundamentals of the proposed model stating that best estimation of the state of material or structural element might be attained, taking into account several stable AES parameters, we defined the following parameter ζ by the dependence:

$$\zeta = A\Delta f_0 c\cdot (\tau_1\, \Delta f \cdot\eta\cdot k^*)^{-1}, \qquad (1)$$

where A is the amplitude of electric AES; Δf is the width of frequency spectrum of AES; Δf_0 is the width of working frequency band of an AE device circuit; η is the sensitivity factor of AE transducer; k^* is the amplification factor AE of AE device circuit; c is the proportionality factor, which takes into account physical and chemical parameters of material and modes of AE measurement.

By using the parameter ζ, we can formulate the criterion of estimation of fracture types as follows:

$$\zeta > m^* \text{ means brittle fracture;} \qquad (2)$$

$$\zeta \le m^* \text{ means ductile fracture;} \qquad (3)$$

where m^* is the constant, found from experimental data.

Conception of design of the portable multi-channel AE system. New conception of design of the AE portable multi-channel system together with its base electronic parts and blocks is presented in Fig. 2. The proposed AE portable system provides a selection, preprocessing and recording of AE signals, storage the obtained data in computer memory for further real-time visualization, postprocessing etc. [16, 20].

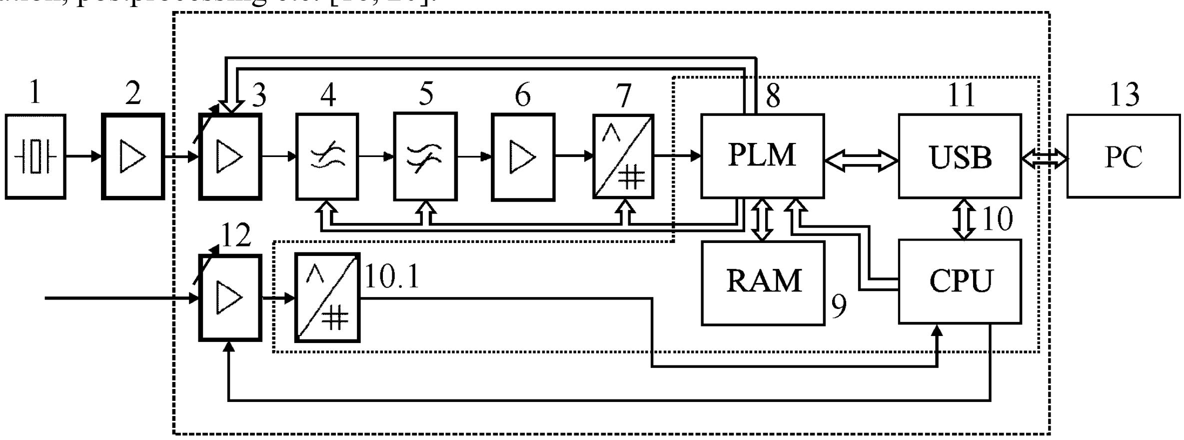


Fig. 2. Chart diagram of AE measuring circuit and parametrical channel of the portable multi-channel system: *1* is the pieso-transducer; *2* is the preamplifier; *3* is the amplifier with a programmable amplification factor; *4* is the low-frequency filter; *5* is the high-frequency filter; *6* is the scaling amplifier; *7* is the analog-to-digital; *8* is the programmable logical integrated circuit; *9* is the operative storage device; *10* is the signaling processor; *11* is the USB port; *12* is the amplifier of parametrical channel; *13* is the personal computer.

We have developed special preamplifier, which amplifies electric signals from the transducer output setting off the signal loss in connection cables, determines the basic signal bandwidth. The rise-time of output signal is 1000 V/μs that allows recording the fast changes in the input signal with the wide broadband.

Main amplification of useful signal in the AE system realizes the amplifier with programmable amplification factor. The program selects the amplification factor with the error ±1% according the processor commands using the serial interface of SPI. The amplification factor can take 64 fixed values. The serial interface was used also for selection the energy-saving mode, when the amplifier does not operate [13].

The AE system allows us to record along with AE data other important parameters, which characterize the state of tested object (temperature, load, pressure, displacement etc.). In most cases, such information could give resistor, capacity, inductive etc. sensors that assembled in electrometric, bridge or some other circuits, or the devices of previous processing (normalizers), which generate a signal as a current or voltage. We developed a parametric channel for amplification of low frequency signals of informative parameters, which realized using the chip of instrumental amplifier with a programmable amplification factor. The amplification factor of this parametric channel is set within the range 70…1280 by operator using the computer keyboard in such a way allowing operatively respond the testing condition.

Verification of the criterion for evaluation of fracture types. For verification of the criterion in order to find the quantitative values of the criterion parameter ζ, we investigated specific features of frequency AES spectrum variation during propagation of elastic waves in structure materials of different types. We recorded AE data by our multi-channel AE system SKOP-8. We found the values of AES attenuation and the variation of spectrum widths depending on prppagation distance.

Our research of amplitude-frequency characteristics of AES have shown that the high-frequency components in the spectrum attenuate considerably greater than high-frequency ones (see Fig. 3) resulting in the spectrum width variation. This circumstance is an important factor that shold be taken into account in diagnostics of structure elements, especially, selecting AE transducers and working frequency band of AE devices.

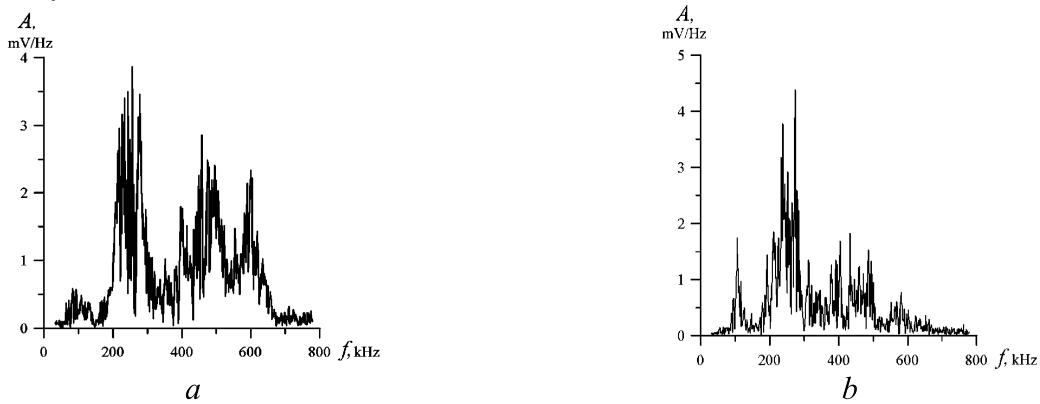


Fig. 3. Amplitude-frequency characteristic of AE signal for propagation of elastic AE waves in the bar of diameter of 50 mm and length 3,12 m of aluminium alloy D16-T. The distances between emitting transducer and receiving transducer were 0,65 m (*a*) and 3,1 m (*b*).

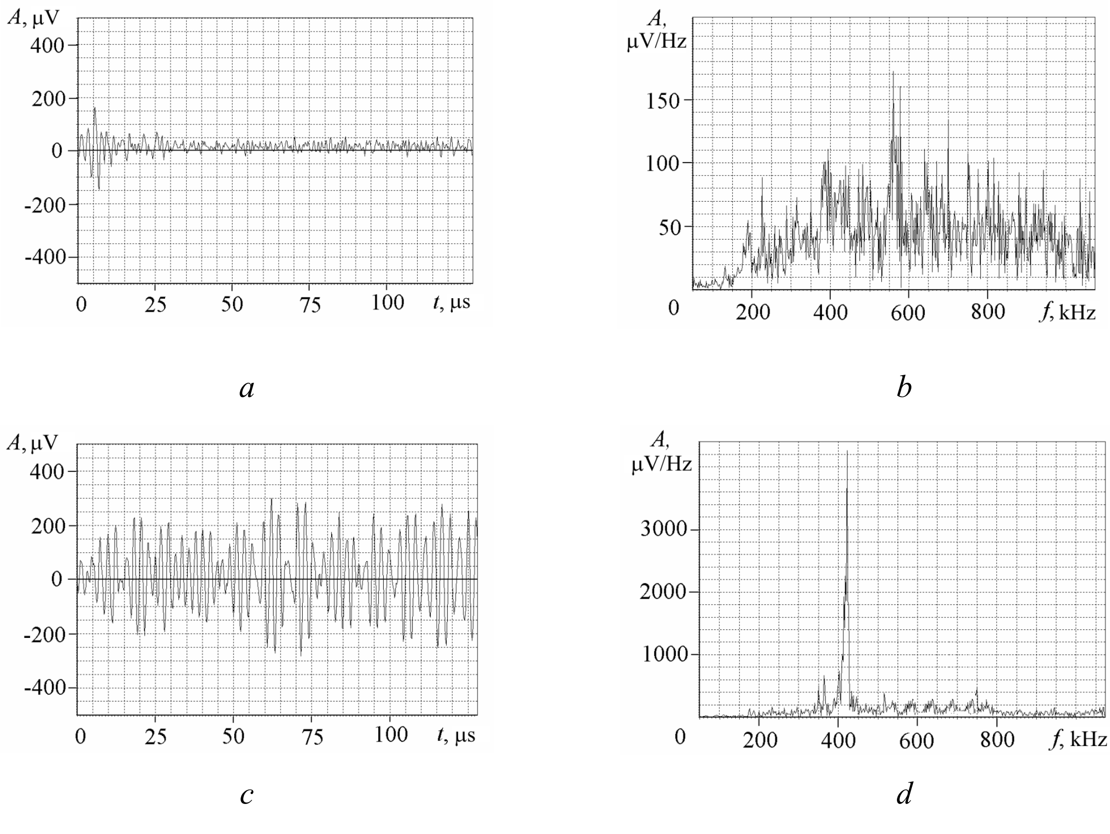


Fig. 4. AE signals during fracture of polyvinyl specimens for applied stress σ = 5,5 MPa (*a, b)* and corundum for applied stress σ = 269 MPa (*c*, *d*): *a*, *c* are the waveforms, *b*, *d* are the spectral distributions.

By using the SKOP-8 we quantitative estimated variation of frequency spectrum of AES and their rise-times (see Fig. 4), which are inherent for brittle and ductile fracture of different structural alloys.

In a result, the technique for distinguishing the fracture types in elements of operation structures by the parameter ζ is proposed. This technique is grounded on following statements:

1. To select the type of AE transducer in accordance with the type the wave that shold be recorded (spatial or surface wave).
2. To determine amplitude-frequency characteristics of AE transducer and its operating frequency band.
3. To determine sensitivity of AE transducer.
4. For measuring AE device to select the proper frequency band in accordance with the operating frequency band of AE transducer.
5. To select an amplification factor of analog circuit of measuring AE channel.
6. To select the allocation of AE transducers accounting for elastic waves attenuation in inspected object.
7. To calibrate the sensitivity of AE transducers after their allocation at inspected object applying Hsu breaking lead technique.
8. To record the AE data from operating inspected object or to excite the elastic waves in the inspected object according to valid standards or other branch documents.
9. To determine proper characteristics of AES that define criterion parameter, namely, the amplitude of envelope, the rise-time, frequency band of the signal.
10. From equation (1), to calculate the value of criterion parameter ζ and compare this value with the criteria for ductile and brittle fracture.
11. To establish according equations (2) and (3) the type of fracture for the current time period.
12. To locate the AE source corresponding to the recorded AE event.
13. To estimate the sizes and spatial orientation of a crack using known analytical dependences or estimate the bulk damaging in localized fracture region.
14. To prepare the test report of tests of this OK.

In Fig. 5 we have shown the classification of structure materials according to their type of fracture that summarize our experimental data.

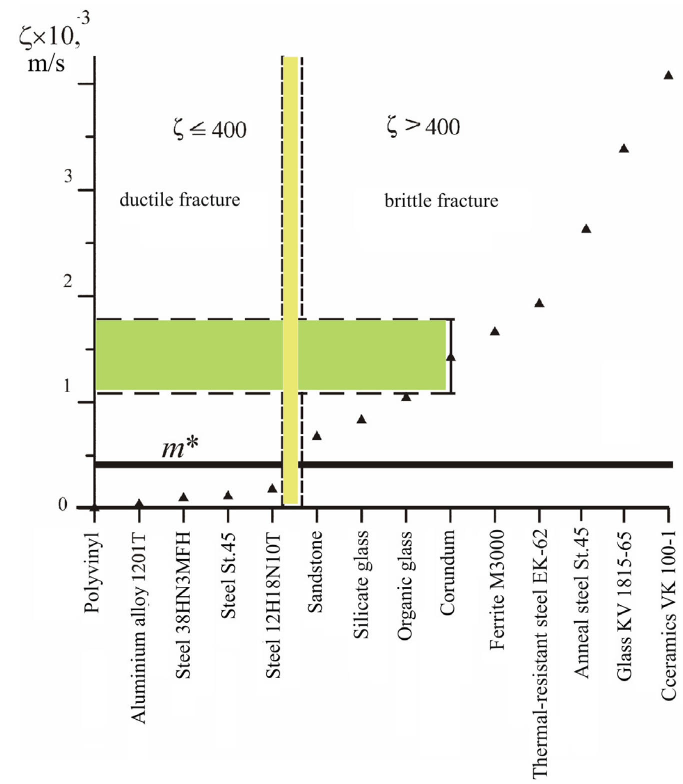


Fig. 5. Classification of the fracture types of some structure materials obtained according to equations (2) and (3).

Applied techniques of AE diagnosing of products and structural elements. The developed techniques allowed to detect most dangerous for structure integrity crack-like defects in structural materials degraded during the long-term operation. These materials are as usual exposed to the simultaneous action of loading, environment and different types of physical fields. The developed techniques in these conditions have shown their high efficiency.

For instance, made by "Tekhnolyuks" ltd the sidewalk hollow RGB light was tested for estimation the safety load capacity for which no crack nucleation and propagation was observed. The AE signals we used as an indicator of fracture. We tested the sidewalk hollow RGB light on the machine UME-10TM under quasi-static loading with average loading rate of 2...3 $kg \times sm^{-2} \times s^{-1}$. The AE transducers were settled on the lateral surfaces of sidewalk light by the elastic ribbon with force of 3...5 N. The results of AE tests have shown that the fracture started at the stress 0,4...0,6 MPa and final failure occurred at the stress 10...12 MPa.

The similar AE researches we conducted for working table (1060x2000x10 mm) of paper-cutting machine of model "SCHNEIDER–SENATOR" 106. This table was made of steel by casting method and contained the repair weld joint. No AE source was detected in this weld joint. Therefore, we recommended to increase the working load on the table to its service value.

Together with State Road research institute (Kyiv) we conducted AE diagnosing of metallic structures in the transport tunnel of highway Kyiv-Chop near Olesko (Lviv region). The maximal value of the testing static load was approximately 200 ton. The analysis of AE results obtained in accordance with the developed techniques has shown no developed critical cracks in the tested cross-section of the tunnel were detected.

Similar joint diagnostic investigation was conducted in order to estimate the state of bridge through the sluice of Kiev cascade of hydropower stations. The test have shown that generation of single AE events occurred mainly during static loading of the bridge by the first, second and third tracks (gross weight of the tracks was 66,3 ton). AES were generated discretely practically uniformly in middle part of the beam. Their amplitudes were below the level, which was determined in laboratory for macrocrack start in the concrete of bridge structure. This fact indicates that the tested beam, which was maximally loaded in with other ones, there is not development of critical cracks, and peak levels of AE signals and their spectral characteristics confirm occuring of local microcracking in component of the reinforced concrete. Formation of these microcracks under the load of 0...90,3 tonne and deflections in the middle part of the beam (the maximal deflection was 0,35 mm) did not affect its strength and fracture toughness.

CONCLUSIONS

1. Our results have shown that most informative parameters of AE diagnostics are amplitude, rise time, width of frequency spectrum of AE signals.
2. We found that the width of frequency spectrum of AE signals varies when elastic waves propagate in a solid due to the substantial attenuation of high-frequency components is greater than 12 dB/m, in the same time for low-frequency components this value lies in the range 2,5...8,0 dB/m.
3. We established that the rise time of AE signals contains the information on mechanisms and dynamics of fracture. Its value lies within the interval $0{,}05 \le \tau_1 \le 2$ μs for brittle fracture and within the range $2 < \tau_1 < 15$ μs for ductile fracture.
4. We developed the criterion for evaluation fracture type, which takes into account a sensitivity and gain-frequency characteristic of AE transducer, mode of operations of analog circuit of the AE measuring system, power and frequency parameters of AE signal.
5. Test results that we obtained for a number of structure materials of different physical structure have shown that the range of criterion parameter ζ variation could be separated as follows: the case $\zeta > 400$ corresponds to brittle fracture and the case $\zeta \le 400$ corresponds to ductile fracture.
6. We developed new conception of analog channel design for measuring AE circuit, which allows to record informative parameters of AE signal without essential distortions. Using this channel, we developed the portable multi-channel AE system and conducted its metrological certification.
7. We proposed the guidelines on AE diagnostics of products and structure elements accounting for both the criterion of fracture type evaluation and developed diagnostical AE system.

References

1. *Andreykiv A.Ye., Lysak N.V.* Method of acoustic emission in fracture processes investigation –Kiev: Naukova dumka, 1989. – 176 p.

2. *Skalsky V.R., Andreykiv O.Ye.* Estimation of bulk damaging of materials by the method of acoustic emission – Lviv: Publ. Center of Franko Lviv State University, 2006. – 330 p.

3. *Skalsky V.R. , Sergienko O.M., Plakhtiy R.M. et al.* Estimation of signals of acoustic emission, caused by formation of penny-shaped crack in viscous-elastic environment // Reliability and strength of buildings. – 2006. – № 27. – P.60 – 66.

4. *Skalsky V.R., Koval P.M.* Some methodological aspects of application of acoustic emission – Lviv: Publ. House Spolom, 2007. – 336 p.

5. *Skalsky V.R., Lotockiy Yu.L., Sulim R.I. et al.* Estimation of attenuation of elastic waves of acoustic emission in concrete and reinforced concrete // Physical methods and facilities for testing environments, materials and products.– Lviv, 2007. – №.12. – P.181 – 187.

6. *Andreykiv A.E., Lysak N.V., Skalsky V.R. et al.* Spectral analysis of acoustic emission from growing crack // Technical diagnostics and non-destructive testing. – 1993. – № 1. – P. 75 – 84.

7. *Muravin G.B., Simkin Ya.V., Merman A.I.* Identification of fracture mechanism in materials by the methods of spectral analysis of acoustic emission signals // Technical diagnostics and non-destructive testing. – 1989. – № 4. – P. 8 – 15.

8. *Ilina S.G., Zabilsky V.V., Merson D.L.* Acoustic emission near-by the limit of fluidity of released staley // Physics of metals and metal science. – 1997. – № 5 – P. 143 – 151.

9. *Tuykin O.R., Ivanov V.I.* Factor analysis of stability of acoustic emission parameters // Russian Journ. Nondestruct. testing. – 1985. – № 8. – P. 39 – 44.

10. *Babak V.P., Filonenko S.F., Kalita V.M.* Formation of acoustic emission signals during straining and fracture of materials // Technological systems. – 2002. – № 1. – P. 26 - 34.

11. *Babak V.P., Filonenko S.F., Kalita V.M.* Modelling of acoustic emission signals during in material // Technological systems. – 2002. – № 3. – P. 77 – 81.

12. *Filonenko S.F., Stakhova A.P., Kravchenko V.G.* Modelling of acoustic emission signals during variation of plastically deformed volume of material // Technological systems. – 2008. – № 1. – P. 22 – 27.

13. *Skalsky V.R., Oliyarnik B.O., Plakhtiy R.M. et al.* Eight-channel portable acoustic emission device // Herald of the National university „Lviv Politekhnika" Radio-electronics and telecommunications. – 2005. – № 534. – P. 55 – 63.

14. *V.R. Skalskiy, Koval P.M., Staschuk P. M. et al.* On-line acoustic emission testing of faults in tank for oil storage // Methods and devices for quality control. – 2005. – № 15. – P. 3 – 8.

15. *Koval P.N., Skalsky V.R, Stashuk P.M.* et al. Acoustic emission inspection of the technical state of bridges // Technical diagnostics and non-destructive testing. – 2006. – № 2. – P. 13 – 19.

16. *Skalsky V.R., Oliyarnik B.O., Plakhtiy R.M et al.* Portable device for acoustic emission diagnostics of objects oil and gas-transport system // Methods and devices for quality control. – 2006. – № 17. – P. 7 – 12.

17. *Skalsky V.R., Sergienko O.M., Selivonchik T.V et al.* Acoustic-emission analysis of the stages of subcritical development of cracks in materials // Materials Sci. – 2007. – № 4. – P. 543 – 553.

18. *Skalsky V.R., Okrepky Yu.S., Plakhtiy R.M.* Acoustic emission during cast-iron fracture // III Sympos. on Fracture Mechanics of Materials and Structures - Augustov June 1-4, 2005. P. 369 – 371.

19. *Skalsky V.R., Sergienko O.M., Plakhtiy R.M.* Estimation of acoustic emission attenuation in the degraded material of pipeline bend section for feed-water of overcritical pressure power units at thermal power plant // 7 Int. Symp. Ukr. Mech.-Engs., Lviv, May 18-20, 2005– P.105.

20. *Skalsky V., Serhiyenko O., Pochapsky Ye., et al.* Portable multi-channel device for acoustic emission monitoring of structures and products // Diagnostyka (Poland). – 2008. – **47**, № 3 – P. 43 – 46.