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APPLICATION OF WAVELET TRANSFORMS FOR THE ANALYSIS OF ACOUSTIC-EMISSION SIGNALS ACCOMPANYING FRACTURE PROCESSES IN MATERIALS (A SURVEY)

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We analyze the results of application of wavelet transforms to the analysis of acoustic-emission signals accompanying fracture processes in structural materials and the data of engineering diagnostics of various industrial objects. The methods used for the identification of the types of fracture processes in materials (steels, alloys, polymers, etc.) with the help of wavelet transforms are characterized. We consider the possibilities of wavelet transformations of acoustic-emission signals for the determination of the mechanisms of fracture in composites and processing of the signals of magnetoacoustic emission. Examples of the tests performed in the Physicomechanical Institute of the Ukrainian National Academy of Sciences and demonstrating the efficiency of wavelet analysis of signals are also presented.

Keywords: acoustic emission, wavelet transform, location of the AE sources, identification of the types of fracture, technical diagnostics.

The acoustic-emission (AE) method is one of a few methods of technical diagnostics (TD) and nondestructive testing (NT) that enables one to observe the initiation and development of defects in the materials of objects in real time. In monitoring the state of high-cost or potentially dangerous equipment, it is important to be able to evaluate the variations of values of the parameters of AE signals as functions of time. For this purpose, it is possible to use the wavelet transforms (WT) of AE signals, which enable one to analyze the fine structure of signals [1]. Applying the WT to signals that are nonstationary in time or inhomogeneous in the space, it is possible not only to determine their general frequency characteristic (distribution of the energy of signal over the frequency components) but also to collect information about certain local coordinates characterized by the manifestation of one or another group of frequency components or their rapid changes.

Wavelet Analysis of AE signals in the Course of TD

A mathematical model of the automated system for TD and prediction of the residual service life of industrial equipment on the basis of complex application of the wavelet analysis and neural-network technologies is well known [2]. The wavelet analysis makes it possible to separate the noise component affecting the accuracy of predictions. As a result, it becomes possible to realize the early detection of deviations of the mechanical characteristics of the product from permissible values. By using neural networks, one can automate the process of monitoring and, hence, substantially decrease the laboriousness of diagnostic procedures.

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The results of application of the WT of AE signals in monitoring the state of tools and machines can be found in the surveys [3–5]. The following directions of application of the WT were distinguished: the time-frequency analysis of signals; removal of noise components from the signals and extraction of weak signals; determination of their characteristics; singular analysis of the state of tool and/or machines; determination of the characteristics of detected damages and defects; evaluation of the degree of wear of the tool, compression of information, and identification of systems.

For the analysis of AE signals in the process of diagnostics of engineering systems and equipment, it is customary to use the discrete or packet WT. Thus, in particular, the wavelet packet transform (WPT) is used to detect AE signals generated by the formation and propagation of cracks, formation of scratches, etc. in the course of monitoring of the state of tribological systems [6, 7]. In the investigation of the contact fatigue of railroad tracks [6] by the proposed method of selection of individual AE events, the process of crack propagation in the track was analyzed and classified. The energy criterion of the WPT of AE signals was used in monitoring the coating of the surfaces of cast-iron–steel tribocouples [7]. The authors of [8] determined the optimal mother wavelet for the WPT according to the Shannon entropy criterion and proposed new methods for the detection of defects in high-speed railroad tracks according to the frequency components of the AE signals.

Rolling bearings are important structural elements of various machines. Their state is monitored in four stages: statistical analysis, diagnostics of defects, determination of their sizes, and prediction of the residual service life. In [9], the authors proposed an efficient modified algorithm for processing AE signals used for the diagnostics of defects in the components of rolling bearings for different rates of performing operations, loading rates, and the sizes of defects based on the optimization of the Kurtosis relation and Shannon entropy for the determination of the optimal wavelet and the application of the WPT.

The work [10] was devoted to the problem of increasing the functional safety of the cars by introducing new methods of diagnostics of the gear box. The authors combined the methods of AE with vibroacoustic measurements and performed a discrete WT (DWT) for the analysis of the data. In this way, they identified the most sensitive diagnostic parameters by using which it is possible to characterize the state of the investigated system better than with the help of the classical approaches.

In [11], the DWT was used for the analysis of the frequency content of AE signals in monitoring the procedure of centerless grinding. The authors established the influence of the surface roughness and geometric parameters of specimens on the frequency parameters of AE signals and proposed efficient methods for the prediction of the surface quality of products and evaluation of errors of grinding.

The authors of [12] developed a new approach to the classification of AE signals appearing in the course of corrosion monitoring. Its important step is the removal of the noise components of signals with the help of WT performed in order to select the useful part of these signals. Reliable and efficient criteria of corrosion detection were proposed according to the results of subsequent analysis of the AE signals with the help of the Random Forest algorithm.

Wavelet Transform in the Problems of Location of AE Sources and Identification of Defects in Structural Materials

In the literature, the application of WT for the location of AE sources [13–24] and identification of defects in structural materials is described fairly comprehensively [25–38].

For the continuous wavelet transform (CBT) of AE signals, the wavelets based on the Gaussian function, e.g., the Gabor wavelet, are used as mother wavelets especially extensively. By using this approach, the authors of [17] improved the procedure of filtering out the noise components from the signals, visualized and separated acoustic modes, determined the distance from the AE source according to a single oscillogram, and found the time of arrival of the signal more precisely. The methods of location of the AE sources with one transducer in thin plates were constructed in [18]. The time of appearance of the characteristic modes was determined according to the maximum coefficients of the Gabor WT. The CWT with Gabor wavelet was used in [30] to identify and evaluate defects in corroded steel, which made it possible to determine the frequency ranges corresponding to some types of defects. The same methods were used in [33]. For a more efficient identification of different mechanisms of fracture of the coatings (transverse cracking, fracture of the coating–matrix bonding), it was proposed to use a frequency that corresponds to the wavelet coefficient with maximum amplitude. For the localization of defects in reinforced-concrete structures, the authors of [24] used a new energy parameter based on the CWT with Gabor wavelet.

The investigations based on the use of some other wavelet functions are also known. Thus, in particular, in [31], the efficiency of the CWT was analyzed on the basis of three wavelets (“Gaussian-27”, “Gaussian-1”, and “Daubechies-40”) and a method was described for the detection and precise identification of AE events in time and location of the sources of signals according to the outflow within the corresponding energy ranges with the help of the “Gauss 27” wavelet. A method intended for the identification of cracks in plates on the basis of the wavelet analysis was presented in [16]. The CWT method was applied to AE signals for the location and determination of crack depths after choosing (in advance) the most efficient mother wavelet, namely, “symmetric-4,” from the collection of wavelets including “coiflet-2”, “orthogonal-6.8”, and “symmetric-4”. In [21], in order to detect defects in a wind-turbine box, the authors proposed a method for a more precise determination of the time of arrival of AE signals based on the WT with Morlet wavelet. The sequence of micromechanisms of fracture in galvanized steel was discovered according to the variations of energy of the CWT with Haar wavelet [34].

The DWT of recorded signals is often used for the detection of AE sources. Thus, in [35], to identify the time of initiation of friction in the rotor, the authors first performed the DWT of AE signals with “Daubechies-20” wavelet (eight levels of decomposition) with removal of the noise components and then the site of friction was found by the cross-correlation method. In [19], for the identification of fatigue cracks at the onset of crack growth, the authors applied the DWT with biorthogonal wavelet (five levels of decomposition) to the AE signals. The application of the AE method for the monitoring of thermal welding was studied in [32]. On the basis of the DWT with “Daubechies-6” wavelet (six levels of decomposition), it was established that the locations and sizes of welding defects can be reproduced by analyzing the variations of the energy levels of decomposition of the AE signals obtained in the course of passing of the welding device over the defective area.

For the detailed analysis of the frequency spectrum of AE signals, the WPT proves to be more efficient. Thus, in particular, in [13], the WPT with “Daubechies-5” mother wavelet and four levels of decomposition, i.e., sixteen wavelet packets, were used to study the propagation of AE signals through the elements of turbines. The authors of [23] used the WPT for the localization of welding defects. The procedure of identification of the micromechanisms of fracture in two-phase steel was developed in [27]. On the basis of the analysis of the frequency range of each level of decomposition of the WPT of AE signals with the “Daubechies” wavelet (three levels of decomposition and eight wavelet packets) and the distribution of energy, it becomes possible to identify various types of defects, such as breaking of ferritic–martensitic bonds and failures of the martensitic phase. A new method for monitoring the state of bearings of rotating machines with the help of WPT based on the “Daubechies-10” wavelet was described in [36]. In [37], a grinding scorch of the material was identified with the help of AE. The properties of AE in the course of thermal expansion were investigated by modeling the thermal consequences of grinding by laser irradiation. According to the results of WPT, it was established that the distribution of energy of the AE signals at a high temperature is concentrated in high-frequency bands. At low temperatures, their distribution is concentrated in low-frequency regions. In the presence of a grinding scorch, the high-frequency characteristics of the AE signals are much more pronounced than in its absence.

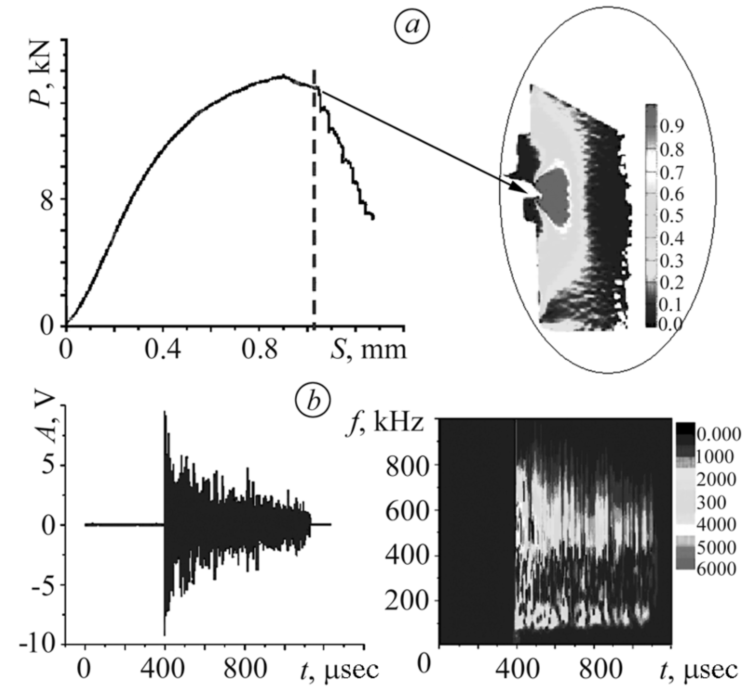

Fig. 1. Load–displacement curves and a fragment of numerical modeling of the crack start (a); the AE signal accompanying the process of crack initiation and its CWT (b) [39].

In [38], one can find a method of two-dimensional WT used for the identification of cracks in plates. The crack depths were quantitatively evaluated by the maximum values and the energy contents of wavelet-coefficients of the WT with "symlet-6" mother function.

The initiation of cracks in aluminum alloys in tension and in the process of fatigue fracture was investigated in [39]. To determine the characteristic features of the AE signals generated in the course of initiation and subsequent growth of a crack, the authors analyzed the fracture diagrams, the amplitudes, and the frequency contents of AE signals in their CWT and compared them with the results of numerical modeling (Fig. 1).

Identification the Mechanisms of Fracture of Composites by Using the WT of AE Signals

The WT of AE signals provides the time localization of their features and, hence, guarantees the efficient identification of the main fracture mechanisms of composites: cracking of the matrix, debonding, exfoliation of fibers from the matrix, development of cracks in fibers, their stretching, etc.

In particular, the classical AE method and the WT of AE signals were used to analyze the specific features of fracture of model composites in [40]. By using the fast Fourier transform (FFT) it was shown that the AE signals with predominant frequency range <100 kHz are generated in the course of fracture of the matrix, the signals with the predominant frequency range 200–300 kHz are generated in the case of exfoliation of the fiber, whereas the signals with the predominant frequency range 400–450 kHz accompanied the fracture of the fiber. To clarify the sequence of mechanisms of fracture of the composites and their duration, the authors applied the CWT based on the Gabor wavelet and analyzed the microfractograms of the specimens. It was shown that the fracture was caused by the violation of the integrity of the fiber at the center of the cross section as a result of which the cracks rapidly propagated along the radial lines in the fiber and in the matrix and caused the complete fracture of the composite. In the case of WT, the duration of the emitted AE signal (its maximum frequency is 20 kHz) corresponding to the process of cracking of the matrix constitutes 35 μsec, while in the case of breaking of the fiber (its maximum frequency is 450 kHz), it is equal to 20 μsec.

The results of investigations of symmetric and asymmetric cracking of the matrix in the middle and surface layers of glass-fiber reinforced composites were presented in [41]. The AE signals generated in the course of cracking of the matrix in multilayer composites were classified by using the generalized results of numerical modeling of the signals, the DWT ("Daubechies-5" wavelet) of modeled signals, the experimentally obtained signals, and the results obtained by the least-squares method.

The procedure of application of the wavelet analysis of AE signals for the investigation of the specific features of fracture processes in composite materials hardened by carbon fibers was described in [42, 43]. To evaluate the AE signals obtained in the course of fracture of composites, the authors used the DWT with 11 levels of decomposition and the "Daubechies-20" wavelet. It was shown that the ninth level characterizes the energy emitted as a result of fracture of the fiber and that the center of the frequency spectrum is close to 300 kHz. Moreover, the eighth level characterizes the energy of breaking of fiber–matrix bonds with center of the frequency spectrum close to 250 kHz. The other sources of signals with higher or lower frequencies and low energies were also detected. Among these sources, the seventh level (with a frequency center close to 110 kHz) is predominant, which characterizes the energy generated as a result of cracking of the matrix.

The model of determination of the group speed as a function of frequency of the transverse mode of normal waves propagating in graphite–epoxy composites on the basis of the analysis of the Gabor wavelet and the examples of its application for the efficient location of the sources of emission of AE signals were described in [44, 45]. By using the frequency dependence of the time of arrival of signals and the angular dependence of the group speed, one can establish more precisely the location of the AE sources for unidirectional and quasiisotropic large flat composite plates.

In [46], the authors studied a more complicated case of presence of the several types of waves propagating in a layer of the composite material. They proposed general methods for the automatic selection of waves in composites with different structures for the WPT of AE signals. It was established that, in this way, it is possible to identify important types of waves, determine the times of their arrival to the primary transducer, and hence, increase the accuracy of location of the sources of emission.

A new algorithm for the location of AE sources and evaluation of the group speed in composite structures was proposed in [47]. This algorithm is based on the difference between the times of arrival of Lamb transverse waves recorded by six primary transducers. The CWT with the complex Morlet wavelet was applied to the AE signals. According to this concept, it is possible to identify the time of arrival of the wave packet and the value of frequency corresponding to it according to the squared amplitude of the maximum wavelet coefficient. To check the algorithm, two different composite structures, namely, a quasiisotropic carbon-fiber-reinforced polymer and a sandwich panel, were investigated. The sites of location of the AE sources and the group speed were determined. The maximum error of location was approximately equal to 2% for the quasiisotropic panel made of a carbon-fiber-reinforced plastic and almost 1% for the plate.

The work [48] is devoted to the application of the AE method for the monitoring of the state of composite materials under the action of abrasive wear. Among the mechanisms of wear of fiber-reinforced composite materials, we can distinguish the following mechanisms: fiber–matrix debonding, rupture of the fiber and displacement of its parts by shear forces, and the removal of particles of the matrix (Fig. 2). For the identification of signals from different mechanisms of wear, the authors used the method of identification of images. To separate the signals caused by specific events in the presence of continuous AE, the authors used a tool for the CWT built in the PACShare Wavelets (PAC) software.

According to the analysis of the frequency features, the low-frequency and long-term signals correspond to the exfoliation of the fiber from the matrix, the high-frequency signals correspond to the rupture of the fiber,

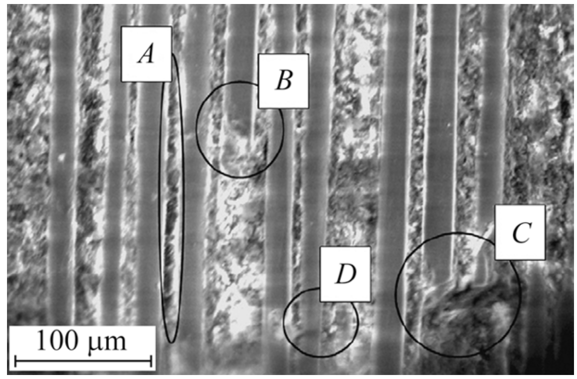

Fig. 2. Different mechanisms of fracture of a glass–polyester disk after the wear tests: (A) fiber–matrix debonding; (B) rupture and displacement of the fiber; (C) displacement of the matrix and the fiber; (D) rupture of the fiber [48].

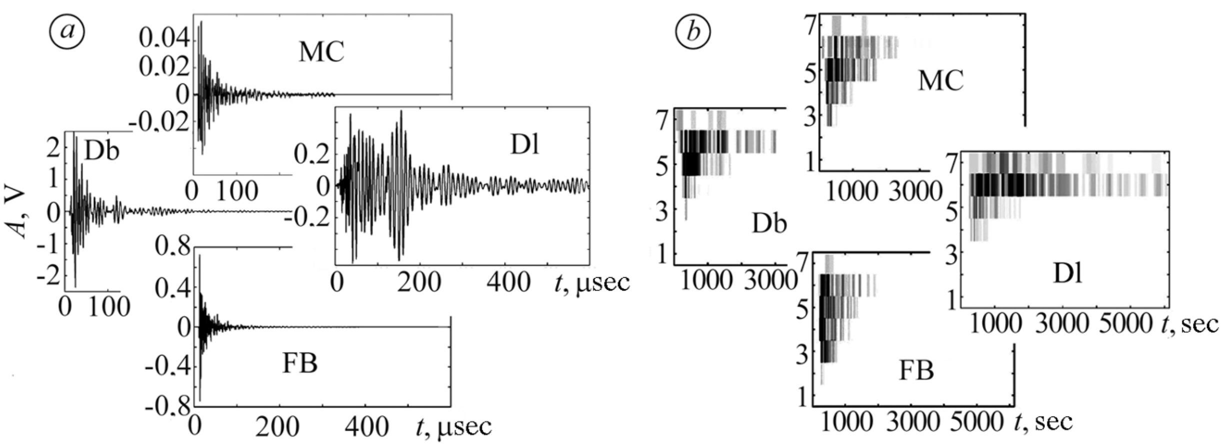

Fig. 3. Typical AE signals generated by different fracture mechanisms (a) and their WT (b) in tension: (MC) cracking of the matrix; (Db) matrix–fiber debonding; (Dl) exfoliation; (FB) rupture of the fiber [48].

and the AE signals of the medium-frequency range correspond to the process of cracking of the matrix (Fig. 3). The signals generated as a result of fracture of the fiber and its exfoliation from the matrix, as well as the hybrid signals combining signals of the former two types, were identified with the help of a neural network.

The method of passive diagnostics for the determination of the frequency characteristics of AE signals in graphite–epoxy composites was described in [49]. By using the DWT (with "Daubechies-4" wavelet and three levels of decomposition), it was established that the frequency range 300–400 kHz corresponds to the cracking of the matrix, while the frequencies lower than 250 kHz correspond to exfoliation. It was also established that, at the end of the fracture processes in these composites, the duration of AE events decreases, while the amplitudes of signals are three times higher than in the case of exfoliation.

In [50], the authors presented the results of application of the multifactor analysis and WT for the identification of the types of fracture of glass-fiber-reinforced composite materials with different structures, namely, of multilayer materials and cross-ply composites. For the CWT and DWT of AE signals with "Daubechies-10" wavelet (five levels of decomposition), the authors proposed new criteria according to which the fracture mechanisms can be identified more efficiently than by the method of clusterization of AE signals.

A complex methodology of postprocessing of the AE signals obtained in the course of testing of the composites was proposed in [51]. For this purpose, the authors used the FFT for the determination of the predominant frequency ranges and the WT ("Daubechies-20" wavelet and six levels of decomposition) aimed at the identification of fracture mechanisms. It was established that about 50% of energy of the AE signals is concentrated on the level of decomposition with a frequency range of 300–400 kHz. Thus, it may correspond to the most widespread mechanism of fracture of the composite, i.e., to the rupture of the fiber.

The WPT was used to evaluate the state of the drilling tool and to study the specific features of fracture of glass-phenolic polymeric composites in drilling [52]. The analysis of the amplitude–frequency characteristics of AE signals demonstrated that, as the number of drilled holes increases, the frequency and amplitude of signals change, which may serve as the indication of deterioration of the state of the tool. As a criterion for its evaluation, according to the results of investigations, it was proposed to use the parameter computed according to the wavelet coefficients of the WPT (four levels of decomposition).

In [53], it was proposed to determine the mass fractions of substances in composites with microcrystalline graphite by the AE and WPT methods. The characteristics of attenuation of the AE signals in composites with various mass fractions of graphite were investigated. The relationships between the attenuation coefficients of energy, the amplitudes of packets of wavelet functions, and the mass fractions were established by using the WPT. It was discovered that, for higher contents of graphite, the rates of attenuation of energy and the amplitudes of packets of wavelet functions are higher. The parameters of attenuation within the frequency range 125–171.85 kHz are most sensitive to the evaluation of mass fractions and the error is equal to 1.8% as compared with 3.9% according to the output signal.

Graphite- and glass-fiber-reinforced composites were studied in [54]. To determine the bending load, the authors used various methods of processing of the AE signals, namely, WT, FFT, and the Choi–Williams transform. It was established that, under the conditions of loading by three-point bending, the WT proves to be the best method that can be used for processing the AE signals.

The fracture of polymeric composites with carbon fibers was investigated in [55]. The correlation between the identified images and the mechanisms of fracture of these composites was established by using a new method for the identification of images based on the coefficients of the CWT, which made it possible to classify defects in these composites. The authors of [56] proposed to use the DWT in order to remove the noise components from the AE signals.

In [57], the authors constructed an algorithm for the identification of defects in composite walls of high-pressure vessels based on analysis of the CWT of AE signals. As a result, the types of waves (symmetric and asymmetric Lamb waves) were selected and their frequency bands were determined.

The specific features of delamination of multilayer fiber-reinforced composites under the action of tensile forces were investigated in [58]. For the analysis and clusterization of the AE signals, the authors used the method of identification of images. Further, on the basis of the results of finite-element modeling, it was established that the obtained three types of AE signals correspond to the following mechanisms of fracture of fiber-reinforced composites: cracking of the matrix, fiber-matrix debonding, and fracture of the fibers. This result was also confirmed by the CWT of the experimental and modeled AE signals.

Wavelet Analysis in Processing the Signals of Magnetoacoustic Emission (MAE)

Note that the MAE signals, just as elastic AE waves, are described by using the theory of random processes. They are characterized by the frequency spectrum that varies with time. This is why, for the analysis of their frequency features, it is more efficient to use the WT.

These investigations are not numerous, which is reflected by a small number of available publications. In particular, in [59], one can find the procedure of evaluation of internal mechanical stresses according to the WT of the MAE signals. It was established that the wavelet coefficients in the frequency-time plane describe

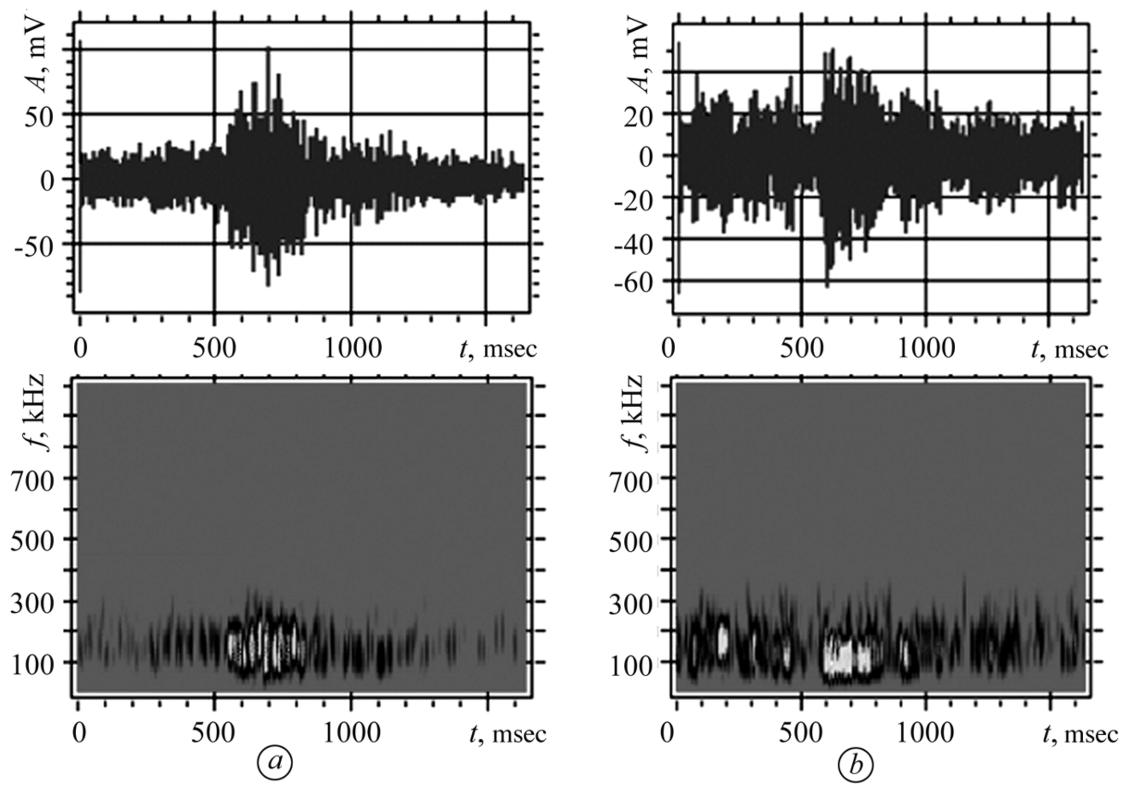

Fig. 4. Typical MAE signals and their wavelet transforms in the course of remagnetization in the directions parallel (a) and perpendicular (b) to the longitudinal direction of the axis of the strip [61].

the characteristic features of signals and, moreover, by analyzing the variations of these signals, it is possible to evaluate the stressed states of structural elements.

The dependences of the Barkhausen noise and MAE signals on plastic strains in plates of Armco iron were investigated in [60]. To detect the changes in the properties of noise signals, the authors performed the multiparameter analysis (FFT, amplitude distribution of signals, and WT). The influence of plastic strains on the rate of generation of MAE signals and their amplitudes was determined.

The specific features of MAE in a strip of 2605SC metallic glass were studied in [61] by the remagnetization of specimens in two perpendicular directions. By using the CWT with Gabor wavelet, the authors discovered the differences between the frequency compositions of the MAE signals depending on the direction of remagnetization relative to the longitudinal axis of the strip: In the case of the parallel direction, the amplitudes of MAE signals are higher, more concentrated in time, and have a more complex frequency structure than in the case of the perpendicular direction (Fig. 4). This can be explained by the difference between the volumes of remagnetization. The authors selected two types of MAE signals by using which it is possible to estimate the homogeneity of the structure of the material.

In [62], by the method of wavelet analysis, the authors established the mean duration of noise (about 10^{-4} sec) in a $Fe_{78}B_{12}Si_9Ni_9$ amorphous alloy. By using a new approach proposed in [63], the Barkhausen noise was processed with the help of fractal analysis based on the WT and the cracks formed in metallic ferromagnetic structures were detected in the early stages of their initiation.

The work [64] is devoted to the diagnostics of thick-walled objects according to the intensity of MAE. It was established that the useful MAE signal (whose intensity in the process of diagnostics under the industrial conditions can be lower than the intensity of the background noise) can be selected by the methods of FFT and wavelet analysis. This filtering method guarantees the possibility of measurements solely of the useful data, which significantly simplifies their analysis and increases the reliability of conclusions.

In [65], the influence of hydrogen on the parameters of MAE signals was investigated with the use of the CWT (Gabor wavelet) and DWT ("symlet-8" wavelet and three levels of decomposition). It was established that, as the magnetic-field strength increases, the maximum values of the wavelet coefficients for the CWT of MAE signals in nickel increase both for the material in the as-received state and after hydrogenation. At the same time, in the presence of hydrogen in nickel, their maximum values are lower than for the nonhydrogenated material by 15–30%. By using the frequency parameters of the CWT and the distribution of energy of the MAE signals for the DWT, it is possible to reproduce physical processes induced in ferromagnetic materials by the changes in the magnetic-field strength and use them as criteria for the evaluation of the influence of hydrogen on structural materials.

Application of the κ Criterion for the Evaluation of the Types of Fracture of Structural Materials

In the investigation of AE in the process of fracture of structural materials, it is important to be able to separate the origins of AE signals and reveal their correspondence to one or another type of fracture. The available methods of identification of the AE signals are efficient in the presence of only two mechanisms of generation of AE, namely, plastic deformation and growth of macrocracks. At the same time, at fracture, various processes can play the role of sources of AE in structural materials within a minor interval. These are the formation of plastic strains, microcracking, cracking of the inclusions, macrofracture, etc. Most of the available criteria used for the identification of the types of fracture are based on the characteristics of the frequency spectrum of signals obtained with the help of the Fourier transform [66]. In view of the high efficiency of WT in the up-to-date processing of AE signals, a new criterion of quantitative evaluation of the types of fracture was proposed in [67–69].

On the basis of the data of theoretical [70, 71] and experimental [67–69, 72–79] investigations, a criterion of identification of the types of macrofracture of structural materials (steels, alloys, composites, and polymers) was formulated and verified by analyzing the amplitude–frequency characteristics of the local specific features of the CWT for the AE signals. For this purpose, the researchers used the following criterion parameter κ:

$$\kappa = \frac{WT_{\max}\Delta f_0}{\Delta f_{\max}}, \tag{1}$$

where $WT_{\max}$ is the maximum wavelet coefficient of a local event in the AE signal, $\Delta f_{\max}$ is the width of the frequency band in the projection of the CWT on the "$WT - f$" plane for the central frequency $f_{\max}$ determined according to the value $0.7WT_{\max}$, and Δf_0 is the width of the working band of measuring AE channel, which depends on the working frequency band of the primary AE transducer (in this case, 200–600 kHz).

Thus, it is possible to quantitatively determine the types of macrofracture of structural materials according to the parameter κ as follows: If $\kappa < 0.1$, then the AE signal characterizes the ductile type of fracture of the material (plastic deformation); if $0.1 \le \kappa < 0.2$, then the AE signal corresponds to the initiation and propagation of microcracks (microcracking); if $\kappa \ge 0.2$, then the AE signal accompanies brittle fracture (formation and growth of macrocracks in structural materials). As the analyzed parameter increases, the probability of fracture of the object of monitoring increases.

On the basis of the CWT and DWT of AE signals, numerous methods were proposed for the evaluation of the types of fracture of materials [65, 67–69, 72–80].

Energy Criterion of Identification of the Types of Macrofracture of Structural Materials

As shown by the practical applications, the proposed κ-criterion is characterized by a narrow range of transition from the ductile to brittle fracture. Hence, it was proposed to estimate the AE signals according to the energy of local maxima of their CWT characterizing each elementary act of fracture. It is known that the formation of the AE signal is affected by the energy released in the course of deformation or fracture and the presence of strains. The level of strains, strain rate, and the mechanism of deformation are connected with the frequency and energy of elastic acoustic waves emitted at fracture. Hence, for the evaluation of AE signals with an aim to identify a certain type of fracture, it is important to take into account not only their frequency features but also the energy characteristics. In [81], one can find the procedure of construction of the energy criterion used for the identification of the types of fracture of materials according to the local features of the CWT of AE signals. As a criterion parameter, the authors used energy of a local pulse of the CWT of AE signal:

$$E_{WT} = \int_{t_1}^{t_2} |WT_a(t)|^2 \, dt , \tag{2}$$

where

$$WT_a(t) = A + Be^{-0.5\left(\frac{t-C}{D}\right)^2}$$

is the approximating function of a local pulse.

We now present several examples of application of the energy criterion for the identification of the types of fracture of structural materials under quasistatic loading.

Specific Features of Fracture of 38KhN3MFA Steel [73, 81]. We performed tensile tests of cylindrical specimens of 38KhN3MFA structural steel quenched at a tempering temperature of 893°K. According to the results of numerical analyses, we constructed the two-parameter distributions of AE signals for different segments of the tensile stress-strain diagram. It was established that, in the early stages of fracture, the activity of formation of microcracks is insignificant as compared with the dislocation mechanisms and increases in the stage of loading, which corresponds to the onset of plastic deformation. Further, we observed an increase in the AE activity. The AE signals corresponding to different types of fracture according to the energy criterion of their identification reveal the intense development of micro- and macrocracking. The last loading stage is characterized by the decrease in the deformed volume and the localization of the zone of deformation (formation of a neck), which is accompanied by the growth and coalescence of microcracks formed earlier and the fracture of the specimen. The values of the energy parameter E_{WT} for various types of fracture of steel are as follows: $0.0001 \le E_{WT} < 0.0009$ for ductile fracture, $0.01 \le E_{WT} < 0.098$ for brittle-ductile fracture, and $0.147 \le E_{WT} < 0.185$ for brittle fracture.

Computing the fractions of energy for different types of fracture, we discovered that, in the case of tension of steel specimens, its largest fraction (68.3%) is released in the case of the ductile and ductile–brittle mechanisms of fracture, i.e., in the presence of plastic strains and microcracking.

Identification of the Types of Fracture for Dental Polymers [76–78, 82]. Polymeric specimens of Protemp™ 4 (3M ESPE, USA), Structur 2SC (VOCO, Germany), Tempron 1-1PKG (GC, Japan), and Acrodent (STOMA Corporation, Ukraine) pharmaceutical materials were investigated under quasistatic tension.

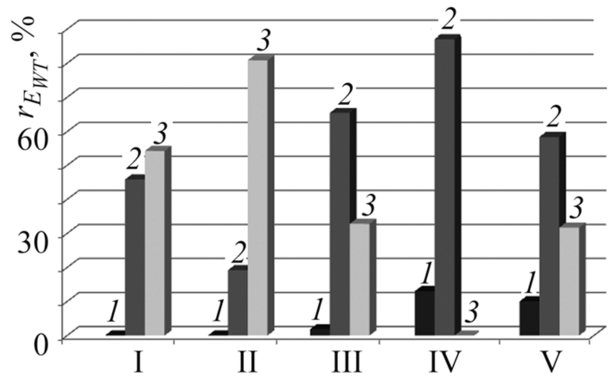

Fig. 5. Distribution of the energy of the types of fracture for different structural materials [81]: (I) corundum; (II) soda glass; (III) 45 steel (quenched); (IV) 45 steel (as-received state); (V) 38KhN3MFA steel; (1) plastic deformation (ductile fracture); (2) microcracking (ductile-brittle fracture); (3) growth of macrocracks (brittle fracture).

We detected the alternation of AE signals corresponding to different types of fracture, which can be interpreted as the development of micro- and macrocracking accompanied by the formation of plastic zones in front of the crack. The application of the energy criterion makes it possible to select the AE events corresponding to plastic deformation for all materials [82]. At the same time, this was not done with the help of the κ-criterion [76–78]. This gives an additional confirmation of the efficiency of energy approach to the identification of the types of fracture and, hence, fracture mechanisms in materials.

Evaluation of the Stages of Fracture of Composite Materials According to the Energy Criterion. The fracture of a hand-shaped glass-fiber composite under quasistatic tension was studied in [75]. By using the time–frequency analysis, we established the relationship between the parameters of the CWT and DWT of AE signals and the mechanisms of fracture of glass-fiber-reinforced composites. Among these mechanisms, we can mention the exfoliation of glass fabric from the matrix, failures of the fibers, cracking of the matrix, stretching of fibers, or the action of shear mechanisms in the matrix. The characteristic features of AE signals whose sources are the exfoliations of glass fabric in the composite can be formulated as follows: a long time of emission (up to 20 μsec), a narrow frequency band in the projection of $WT - f$ at the time of attainment of $WT_{\max}$ (65–75 kHz), the range of values of the energy parameter $0.021 \le E_{WT} < 0.265$, and the maximum energy concentrated in the frequency range 125–500 kHz. The specific features of the AE signals hypothetically accompanying the stretching of fibers or the shear mechanisms in the matrix are short durations (up to 10 μsec), a wide frequency band in the projection of $WT - f$ at the time of attainment of the value $WT_{\max}$ (230–270 kHz), and the range of the criterion parameter $0.005 \le E_{WT} < 0.1$. For the AE signals generated as a result of fracture of the glass fiber, the frequency range 400–500 kHz is predominant, the time of measurement exceeds 20 μsec, and the energy parameter $E_{WT} \ge 0.389$.

In Fig. 5, we show the characteristic distributions of energies for some structural materials for their types of fracture [81].

According to the results of experimental investigations, we established a generalized energy criterion for the identification of the types of fracture: for $E_{WT} < 0.01$, we get the ductile fracture (plastic deformation); for $0.01 \le E_{WT} < 0.1$, we get the ductile-brittle fracture (microcracking), and for $E_{WT} \ge 0.1$, we have the brittle fracture (growth of macrocracks). As compared with the known methods, the criterion provides a higher quality of identification of the types of fracture.

CONCLUSIONS

Thus, the WT turned to be efficient for the analysis of AE signals in the case of diagnostics of engineering objects and identification of the types and mechanisms of fracture of structural materials of different structures. This is why the methods constructed on the basis of the WT of AE signals promote the efficient nondestructive testing and prevention of the premature fractures of structures and their elements.

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