Methodical principles of recognition different source types in an acoustic-emission testing of metal objects

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Abstract. This paper presents issues of identification of various AE sources in order to increase the information value of AE method. This task is especially relevant for complex objects, when factors that affect an acoustic path on an object of testing significantly affect parameters of signals recorded by sensor. Correlation criteria, sensitive to type of AE source in metal objects is determined in the article.

1. Introduction

Acoustic emission testing of metal products and structures proved to be a reliable method of detecting developing defects, which helps to prevent further destruction of objects. However, defect types (fatigue cracks, corrosion defects, etc.) often cannot be identified in process of loading and AE testing of objects.

Recognition of defect types is of crucial importance in testing, since the criteria for assessing the state of objects always come from certain causes and form of detected defects. However, if access to a site with a defect is limited or even impossible, it is difficult to determine the type of defect by another method of nondestructive testing. For such cases, it is necessary to recognize the process of destruction according to the parameters of AE signals. The problem of using stream parameters of AE (acoustic emission count, energy of AE, mean AE energy, etc.) is that they have different regularities for different sources [1, 2]. In addition, expansion of fatigue cracks or plastic deformations at different stages of development are formed by various micro processes [3].

Therefore, the purpose of this article is to attempt to identify criteria that will allow us to determine a type of the signal's source. The presented researches are a continuation of the analysis of AE information presented in articles devoted to straining experiments of low-carbon and low-alloy steels [4, 5].

2. Modeling criteria for the recognition of defects

At the first stage of researches, we stimulated AE signals through an object of testing from source to sensor. The source is an impulse from a crack increment generated perpendicularly to a surface in different directions. The diagram on the Figure 1 showing direction of longitudinal (l) and transverse (t) waves propagating vertically from the crack in the object with width (h).

In the simulation, we used formulas that describe distribution of amplitude values for longitudinal and transverse waves in a plane normal to a plane of crack from [6]:

$$\boldsymbol{u_l(\theta)} = \frac{\boldsymbol{f(\Delta S)\Delta h k_l}}{\boldsymbol{4\pi\mu r}} \cdot \left(\frac{C_t}{C_l}\right)^{\boldsymbol{2}} \cdot \boldsymbol{cos^2(\theta) e^{-\delta r}}, \tag{1}$$

$$\boldsymbol{u_t(\theta)} = \frac{\boldsymbol{f(\Delta S)\Delta h k_l}}{\boldsymbol{4\pi\mu r}} \cdot \boldsymbol{sin(\theta)\, cos^2(\theta)\, e^{-\delta r}}, \tag{2}$$

where *f(ΔS)* – function dependent on a density of forces and the area of crack increment ΔS; θ – angle between deflection of the longitudinal wave and direction of crack development; r – distance to the sensor; Δh – increment in width; k_l – wavenumber; μ – Lame second parameter; C_t и C_l – velocity of longitudinal and transverse waves, δ – damping ratio. Integration of the signal over the area of the receiving transducer allows us to determine the change in the amplitude of the signal without taking into account distortion caused by the frequency response of the transducer.

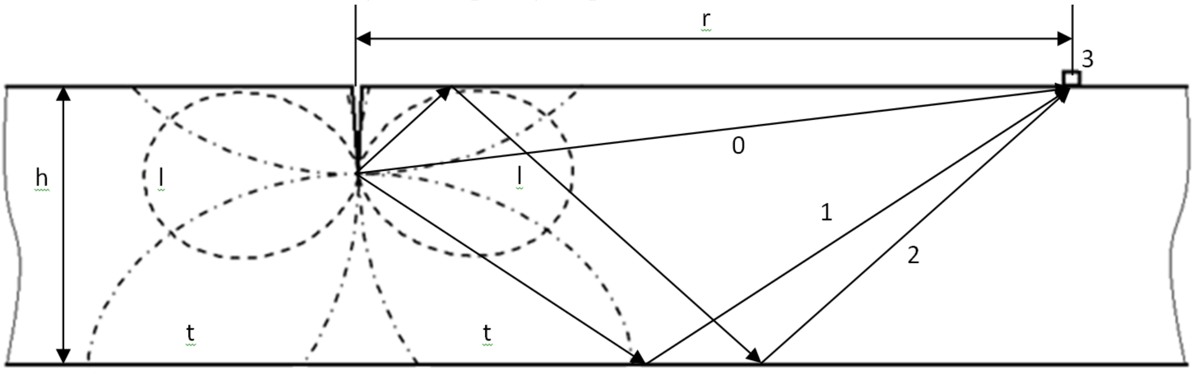

Figure 1. Diagram shows direction of waves (0-2) propagating vertically from the crack by area ΔS and to the receiving sensor 3.

When a crack develops in the vertical direction, each subsequent act of increment differs by coordinates and quantity of released energy. Also, the direction of crack propagation can change. In this case, the simulation showed that a packet of acoustic waves differ only slightly, if radiation of acoustic waves does not change. When elastic and plastic deformation develops in the object of testing a mechanism of formation of each act of AE, coordinates and direction of radiation begin to differ much more than in a growing crack. When two different signals from one source superposed a cross-correlation coefficient can be quantitative characteristic of the convergence of waveforms:

$$k_{ij} = \left[\frac{\sum_{\substack{i-1,\\ j=1+S}}^{n} \left(a_i - \bar{a}_i\right)\left(a_j - \bar{a}_j\right)}{n \cdot \delta_i \cdot \delta_j} \right] \to \max \quad , \tag{3}$$

where n – the total number of discrete values of the signal (in our case frequency of the signal 2 MHz); a_i and a_j – amplitude values of two signals at each point i; $\boldsymbol{\bar{a}_i}$ и $\boldsymbol{\bar{a}_j}$ – the medium values of an amplitude of i and j signals from the source.

When testing sources, signals from the source will show the correlation between maximum amplitudes of the detected signals. Simulation of signals for a pair of sensors with varying source parameters in a small range (up to 10%) by formulas (1) and (2) confirms this statement. Then, it is possible to determine the correlation coefficient of the maximum amplitude values for all signals with five or more signals from one source, received during the test:

$$\boldsymbol{k_U} = \frac{\sum_{i=1}^{N}(\boldsymbol{U_{1i}}-\boldsymbol{U_{1}}_{\text{cp}})(\boldsymbol{U_{2i}}-\boldsymbol{U_{2}}_{\text{cp}})}{\sqrt{\sum_{i=1}^{N}(\boldsymbol{U_{1i}}-\boldsymbol{U_{1}}_{\text{cp}})^2}\sqrt{\sum_{i=1}^{N}(\boldsymbol{U_{2i}}-\boldsymbol{U_{2}}_{\text{cp}})^2}}, \quad (4)$$

where N – number of signals from the source; U_{1i} и U_{2i} – the maximum amplitude of i signal received by the first two sensors closest to the source; $U_{1\text{cp}}$ и $U_{2\text{cp}}$ – the average value of maximum amplitude received by the first two sensors closest to the source. It should be noted that a limited range of amplitudes (for example, 14 or 20 dB) should be used to analyze the parameter k_U. Because large ranges in values can cause a small number of signals with large amplitude to substantially distort the value of the parameter.

3. The conditions of obtaining of experimental data

At the next stage, experimental researches were performed on objects with and without V-shaped stress concentrations. Objects were made of low-alloy and low-carbon steel. Some of the objects were subjected to cyclic loading in area around stress concentration in order to obtain cracks. Then all objects were subjected to static loading with velocity 0.5 ... 2 mm / min until fracture occurred. Two or four receiving transducers were installed on the objects in order to locate cracks. Figure 2.

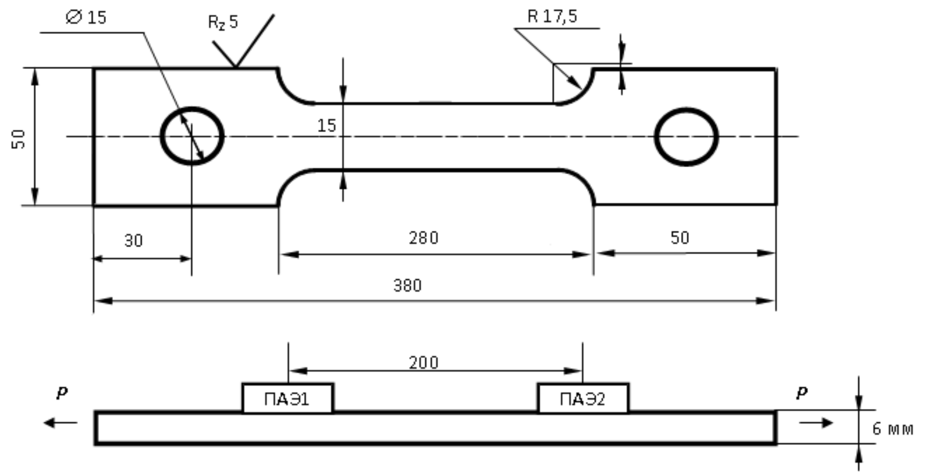

Figure 2. Overall dimensions of the test objects without stress concentrations and scheme of receiving transducers positioning.

Signals from the cracks were determined from a total array of recorded AE signals. Also correlation parameters were analyzed.

The first parameter is the average value of cross-correlation coefficient of all signals from one source received by the transducer $k_{(ij)m}$ in the load range 0,8…1P_j:

$$\boldsymbol{k_{(ij)m}} = \frac{2\sum_{1}^{i=N-1}\left(\sum_{2}^{j=N}\boldsymbol{k_{ij}}\right)}{\boldsymbol{N}\cdot(\boldsymbol{N}-\boldsymbol{1})} \quad (5)$$

where N– number of signal corresponding to the maximum load in a selected range; i and j –number of signals in a preselected range, i varies from 1 to N. We can determine the coefficient in different areas if we analyze parameters of AE signals while changing region of loading. The parameter is most useful, since it can be used to control real objects, when main AE information is recorded at loads that exceed working ones by the value up to 25 % [7], if we take into account Kaiser effect.

4. Analysis of the obtained results

Elastic deformation is accompanied by random distribution of signals and low coefficient k_{ij} - less than 0.3 for all signals. This indicates that local acts of AE in a combination of factors - a mechanism of wave formation, radiation pattern, coordinates - are significantly different and do not repeat in the elastic region. It follows that recording signals on short intervals with k_{ij} above 0,5 seems very unlikely.

Construction of a graphic connection of maximum amplitudes received by two closest to the source sensors allows us to see importance of correlation between these parameters. As shown by the analysis of the AE signals received from deformations in the elastic region (Figure 3a), the coefficient k_U varies from 0.5 to 0.8, depending on which volume of the object is analyzed.

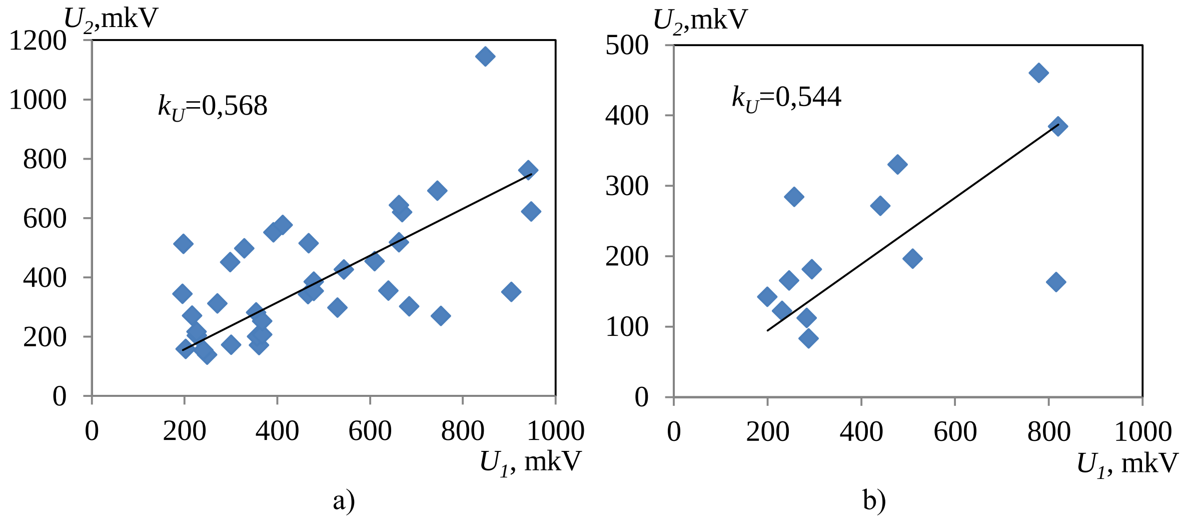

Figure 3. Distribution of AE signals as a function of the maximum amplitude of the signals received by two sensors closest to the source in the region of elastic (a) and plastic (b) deformation.

Considering a low concentration of signals of the elastic region as a single source, arises the problem of identifying such a source on a real object.

Results of tests in the region of plastic deformation similar to results in region of elastic deformation. However, coefficient k_{ij} is higher than 0.4 in some groups of signals. The number of signals in a group and the number of such groups can be up to five depending on the duration of deformation. However, in general, the medium value of the coefficient k_{ij} is below 0.35.

The coefficient k_U in the region of plastic deformation slightly lower than in the region of elastic deformation, as can be seen in Fig. 3b. This indicates that new mechanisms are generated as sources in the local area of plastic deformation, which is known from the literature on deformation [8].

When the object with a V-shaped stress concentrations is loaded, we receive signals from the region of crack development, which have the dynamics of change in a medium coefficient $k_{(ij)m}$ calculated by the formula 5 (Figure 4). As can be seen from the figure, signals in the first stage of the test have a low correlation coefficient. Transition from elastic to plastic deformation is accompanied by an increase in the coefficient $k_{(ij)m}$ above the value of 0.7, which stably remains within 0.7 ... 0.9 until the hardening stage. At the hardening stage, before the fracture, the coefficient $k_{(ij)m}$ gradually decreases to values of 0.3 ... 0.4. Before destruction, the coefficient $k_{(ij)m}$ is increased by a small value.

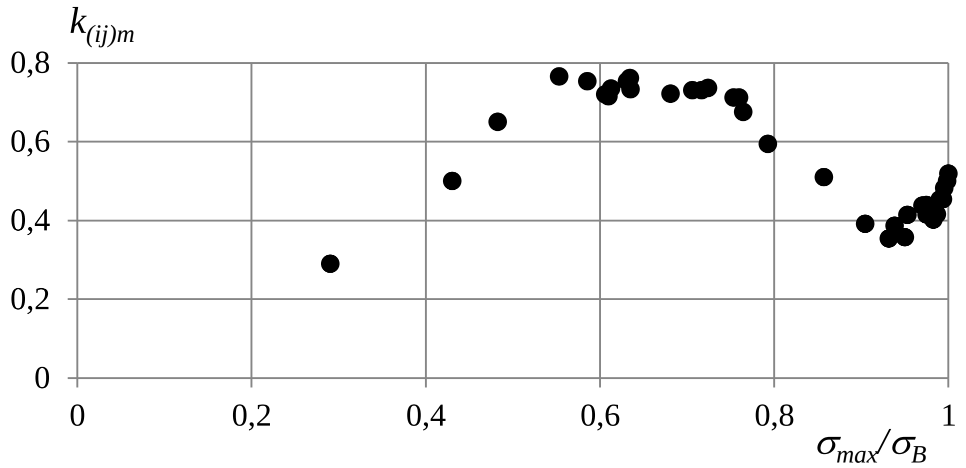

Figure 4. Dynamics of change of the correlation parameter $k_{(ij)m}$ of object with stress concentration under static loading.

To confirm efficiency of the correlation parameter in identification of cracks, additional tests of objects with stress concentrations were conducted. The area of the stress concentration was loaded with a bending load. At the same time cyclic load of 5000 ... 10000 cycles were applied, with a load of P_c = 25 kN, as well as static loading with an increase by 1.25 P_c. Results of loading showed that the cross-correlation coefficient $k_{(ij)m}$ increases at the stage of crack formation, as shown in Fig. 4. The coefficient has the maximum values at the stage of stable growth of crack. Before destruction, the coefficient slowly decreases. With stress concentration factor increasing and $k_{(ij)m}$ decreasing groups (clusters) of signals with a high cross-correlation coefficient formed within a vertex of crack.

The presence of a crack forms AE signals with a higher cross-correlation coefficient compared to the stages of elastic and plastic deformation. So this coefficient can be used to recognize developing cracks from other types of sources. Variety of local fracture processes at an apex of the developed crack leads to decrease in the coefficient $k_{(ij)m}$ when object transfers to stable plastic deformation.

After analyzing the coefficient k_U, it was found that the developing cracks at different stages have a relatively high correlation between the maximum signal amplitudes from one act of AE received by different transducers (Figure 5). In this case, the dependence is stable when calculating the coefficient k_U for different pairs of receiving transducers. But the highest values are typical for receivers closest to the source.

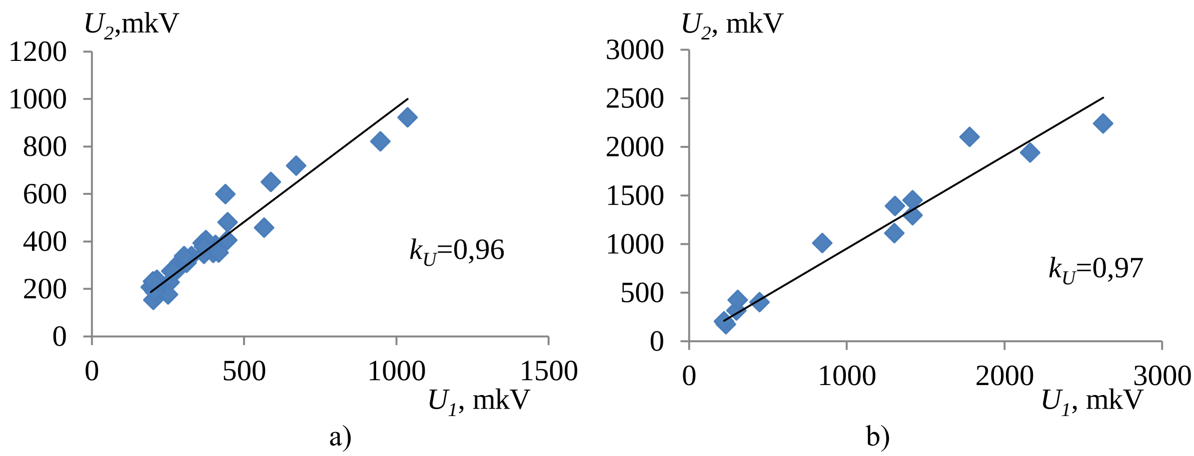

Figure 5. Correlation between maximum amplitudes of signals received by different AE sensors at stages of steady (a) and accelerated (b) crack growth.

Proceeding from the fact that different stages of plastic deformation or development of a crack are described by different formulas, an additional parameter comes to necessity. This parameter allows separating the elastic deformation from plastic deformation, and new cracks from developed ones. Therefore, the area of the source S_n and its concentration coefficient C_n are most important parameters of AE which describe type and size of the source. Concentration coefficient determined by the formula:

$$\boldsymbol{C_n} = \frac{\boldsymbol{N_n}}{\boldsymbol{S_n}}, \tag{6}$$

where N_n – a number of localized events of the n-th source; S_n is determined from the calculated coordinates of all events recorded from the source.

The source concentration coefficient always allows determining size of the area of the testing object. For cast parts, the concentration coefficient is a determining factor when identifying sources with a large flow of AE signals. Also this allows recognizing areas of plastic deformation or other defective structures. However, C_n is a parameter that varies quite strongly for defects of the same type, depending on the concentration of stresses and acoustic properties of a material, which may distort parameters of recorded signals and affect an accuracy of determining an arrival time of the signal to a receiving transducer.

In the analysis of elastic deformation, the area of sources is large. It strongly depends on the type of loading and has a very low concentration coefficient C_n. So in the analysis of plastic deformation, the area of the source is substantially reduced, and the concentration is increased, which makes it possible to distinguish these types of sources.

When testing samples with stress concentrations, the analysis of the parameters S_n and C_n showed that they will vary at different stages of the development of cracks, and this described in known physical literature [3, 8]. Figure 5 shows a distribution of coordinates of cracks at different stages of development. As can be seen, an increase in the region with a high concentration of stresses during the development of the crack increases both the area S_n of the source and its concentration C_n.

5. Conclusions

According to the research results as recognition criteria of AE sources were used:
- medium cross-correlation coefficient of AE signals arriving at one transducer at different times of testing k_{ij};
- cross correlation coefficient of the maximum amplitude of AE signals arriving at different sensors;
- area and concentration of the source.

Thus, it becomes possible to identify different developing AE sources depending on determined values of the input parameters k_{ij}, k_U, S_n and C_n. Based on the values of the coefficients k_{ij}, k_U, S_n and C_n, it is possible to construct an algorithm for identifying each of the listed source types. After identifying the type of source according to the energy parameters of each particular source, we can determine the degree of its development.

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