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INSTRUMENTATION FOR MAGNETOACOUSTIC EMISSION DIAGNOSTICS OF FERROMAGNETIC MATERIALS

The summary. *A promising method for technical diagnostics of materials which employs the signals of magnetoelastic acoustic emission (MAE) has been described. The results of the numerical modeling of the parameters of the U-shaped electric magnet designed for excitation of the alternating magnetic field that would produce MAE signals in ferromagnetic materials are presented. The principles of a PC-operated measuring system designed for MAE signals acquisition, processing and logging has been outlined.*

Key words*: technical diagnostics, magnetoelastic acoustic emission, electromagnet, measuring system.*

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ТЕХНІЧНІ ЗАСОБИ ДЛЯ ДІАГНОСТИКИ ФЕРОМАГНЕТНИХ МАТЕРІАЛІВ МЕТОДОМ МАГНЕТОАКУСТИЧНОЇ ЕМІСІЇ

Резюме. *Описано перспективний метод технічного діагностування матеріалів із використанням сигналів магнетопружної акустичної емісії (МАЕ). Представлено результати числового розрахунку параметрів П-подібного електромагнета, призначеного для збудження з допомогою магнетного поля сигналів МАЕ у феромагнетних матеріалах. Представлено комп'ютеризовану вимірювальну систему, яка призначена для відбору, обробки та реєстрації сигналів МАЕ.*

Ключові слова*: технічне діагностування, магнетопружна акустична емісія, електромагнет, вимірювальна система.*

Formulation of the problem. There is a growing need for the technical diagnostics of the ageed industrial equipment and structures and, hence, there is a need for reliable methods of non-destructive testing and evaluation equipped with proper instrumentation, which is able to detect the degraded volumes of material and prevent the catastrophic failures of such equipment.

Magnetic NDE methods for detection of deformation – state of the art. Electromagnetic instrumentation for measurements of stresses and plastic deformations has been used for technical diagnostics of materials that work in various structures and equipment. These instruments employ magnetoelastic effect, which is a change in magnetic properties of a ferromagnetic material as a result of applied mechanical stress. Magnetoelastic effect is employed also in magnetoelastic and magnetoanisotropic transducers [1]. However, these methods exhibit low accuracy that limits their applications, especially in the cases when the material's topmost layers (less that 0.2 mm) differ from the bulk of metal due to cold work or chemical alteration (nitriding, carburization or any other case hardening treatment).

Such difficulties are experienced also by the systems that employ the Barkhausen effect, e.g. StressScan, PollScan. Electromagnetic waves generated during Barkhausen jumps are of high frequency, which usually makes this technique to be confined to less than 0.2 mm. Only under special laboratory conditions can the information depth be increased to 2 mm. Another issue that cripples reliability of stress evaluation with the help of electromagnetic fields is magnetomechanical hysteresis and attempts to employ only a single parameter like coercive force or residual magnetization, examples being the systems based on “magnetic memory” [2, 3].

Much more promising seems the method of magnetoelastic acoustic emission (MAE) that is based on the effect of generation of elastic waves during magnetization of ferromagnetic materials. Contrary to the Barkhausen effect, which is confined to a shallow surface layer, method of MAE has a much deeper informative depth since the elastic acoustic waves can easily travel from the depth of a structural material with negligible attenuation. MAE is induced by jumping of the 90° domain walls, which is manifested as magnetostriction [4]. The first publication about experimental detection of elastic waves during reversible magnetization appeared in 1974 [5], though the method was developed later [6, 7].

Informative parameters of MAE signals (total count, total sum of impulses’ amplitudes, power, root meat square voltage, etc.) depend on the influence of the changing magnetic field (its strength, frequency, form) on the domain structure of ferromagnetic material and, thus, can reflect the structural changes brought about by heat treatment, plastic deformation, residual stresses, absorbed hydrogen, etc., seemingly with plastic deformation having the strongest influence [8-10]. Thus, MAE depends on the degree of material’s degradation and might be a sensitive tool for non-destructive evaluation of the aged structures, but the MAE method itself is still lacking deep theoretical grounds due to the limitations in the experimental data, which heavily depends on the parameters of the employed instrumentation [6-11].

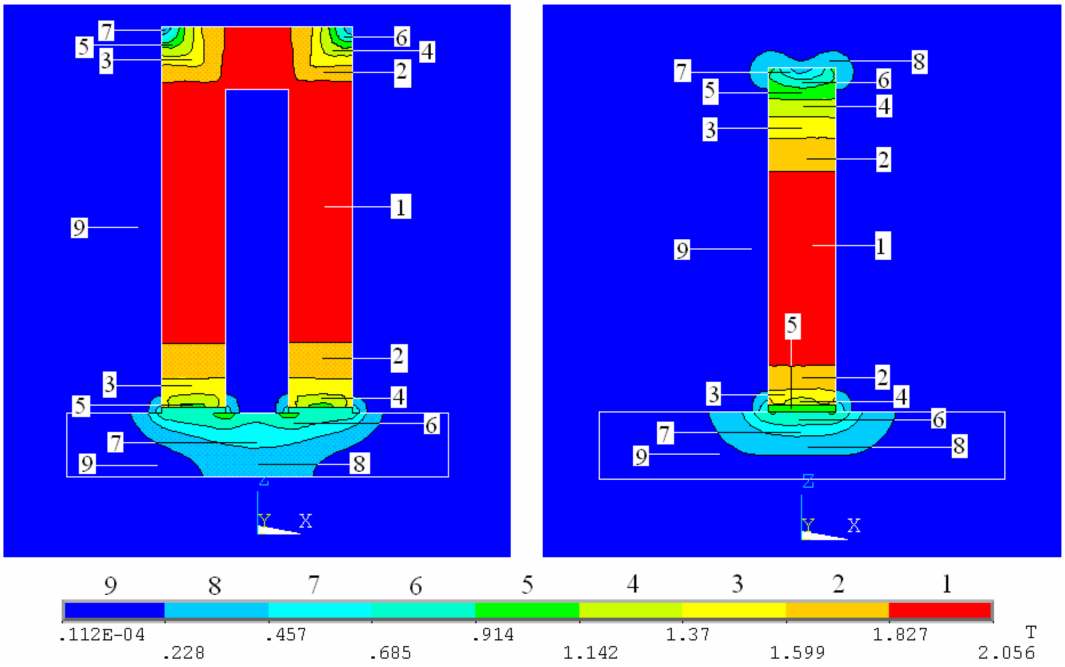
Objective. The goal of our work was to develop a high-quality MAE measuring system, which would allow establishing the correlation between the MAE signal parameters and the parameters of the material, thus allowing also a reliable evaluation of the physical condition of structures and equipment made of ferromagnetic materials.

The principles of the MAE diagnostics of materials. The MAE diagnostic instrumentation is made of two parts: magnetic and acoustic [12-13]. Magnetic part consists of an electromagnet usually of the U-shape and a generator. Acoustic part consists of an acoustic emission sensor, preamplifier and data acquisition-processing-logging system. Electromagnet placed at a certain small distance from the surface of the inspected material and powered with alternating current of certain parameters (form, frequency and amplitude) induces in the volume of the material under the electromagnet poles the magnetization changes, which by their discrete nature are accompanied with acoustic waves. These waves reach the surface of the material causing its displacement. For measuring such displacements an acoustic emission sensor is placed in the vicinity of the electromagnet, so it is able to convert the movements of the surface into electric signal which is further processed by the signal processing system. When the magnet is moved along the surface of metal the electric MAE signals are being recorded. The recorded MAE data is being standardized by incorporating the attenuation coefficients for the elastic waves (obtained from the laboratory study of the pristine and the aged material) and the distance the waves have traveled from the location of MAE under the magnet to the sensor. Since the recorded MAE signals reflect, on the one hand, the structural changes in the material and, on the other, attenuation of the elastic waves with traveled distance, which is also a function of materials degradation, the degraded locations of the aged structures or equipment could be found.

Such procedure requires no additional mechanical treatment of the surface and does not require the application of excessive mechanical stress, which is the case for the standard acoustic emission diagnostics of materials. This makes the MAE method much more time- and cost-effective with no negative consequences related to the overloading of metal in order to propagate the existing cracks in the material, as the acoustic emission method has.

Engineering of the U-shaped electromagnet. The application of MAE diagnostics requires reversal magnetization of certain volumes of a diagnosed material with spatial resolution and the depth of magnetization being the most important parameters. Thus, a requirement for engineering of the electromagnet with certain optimized magnetization and exploitation parameters including the parameters of the coil (type of wire, number of turns, number of layers, etc.) and of the core (material, geometry, design) which would result in specific size, weight, distance between the poles, consumed current, etc.

Previously we reported on the numerical modeling of distribution in time and space of magnetization in a square cut (60x60 mm) of a plate 10 mm thick made of typical carbon steel grade 30 in the magnetic field induced by the U-type and by the solenoid (I-type) electric magnets [14]. It has been established that for the U-type the magnetized volume is better localized and expands deeper (Figure 1). For instance, for the I-type the magnetization at 6 mm depth is about 0.26 T, while for the U-type magnet it is about 0.45 T, which is 1.73 times higher. This makes the U-type magnet more effective in sensing the bulk degradation of thick elements, considering such objects as natural gas transmission pipelines which thickness reaches few centimeters.



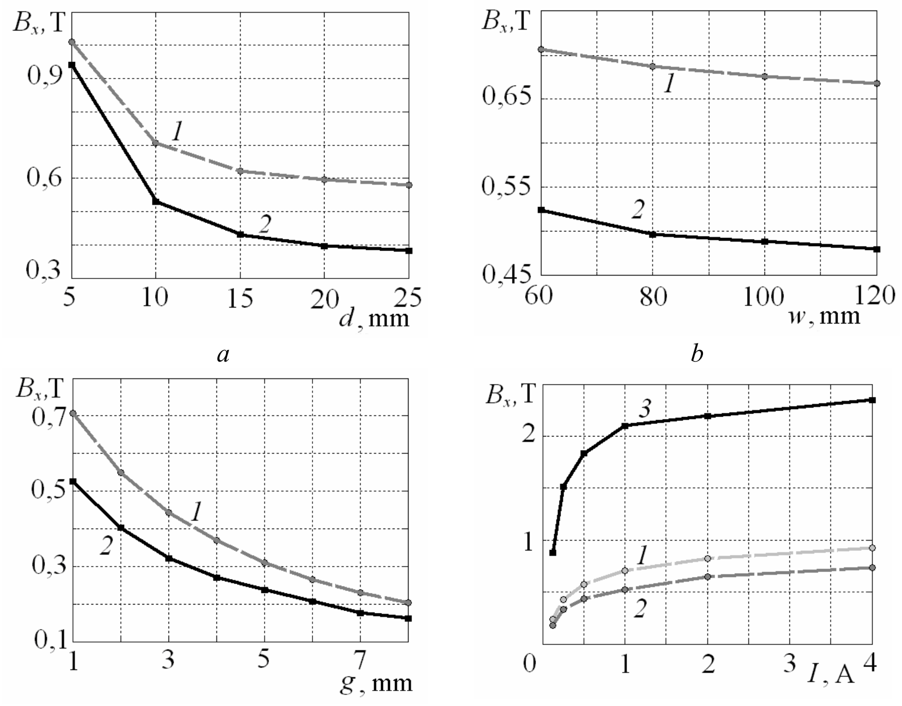
a *b*

Figure 1. Distribution of the magnitude of the magnetization vector in the plane *XOZ*: *a* – for the U-type electromagnet and *b* – for the I-type electromagnet

Additional studies have been conducted regarding the distribution of the magnetic field in the case of a U-type magnet. Figure 2 depicts the dependencies of the B_x component along the *OZ* axis on the thickness *d* of the ferromagnetic material (*a*), its width *w* (*b*), air gap thickness *g* (*c*), and the magnetizing current *I* (*d*). These results suggest that the level of magnetization B_x along the *OZ* axis weakly depends on the specimen width if *w* ranges from 60 to 120 mm. Increasing the air gap (Figure 2b) between the sample and the magnet core from 1 to 8 mm, causes magnetization B_x along the *OZ* axis to drop from 0.7 T to 0.2 T at the depth of 1 mm and from 0.53 T to 0.16 T at the depth of 4 mm.

From Figure 2d it could be deduced that due to the nonlinearity of the $B_x(I)$ dependency, an upper value of the current through the winding of the electromagnet (we would say about 1A in our case) could be selected, above which magnetization of the material increases slightly and thus any further increase of the magnetizing current is ineffective.

In order to optimize the parameters of the U-type electromagnet (that would be able to magnetize a ferromagnetic sample of certain thickness), including geometry of the core, the type of the core material, number of turns, and the amplitude of the magnetizing current, some additional experimental studies have been conducted. Specifically, we studied MAE during reversible magnetization of a steel plate sized 240x30x2 mm that was placed in the solenoid with 55 mm in diameter and 300 mm in length with 1500 turns of winding with a sinusoidal form of magnetizing current. The obtained dependencies of the sum of amplitudes of the MAE signal induced under these conditions versus magnetizing current were recalculated into the dependency versus the amplitude of magnetization, employing the numerical modeling, as has been described previously [10]. Figure 3 depicts this relationship, which suggests that the effective generation of MAE is confined to the upper values of magnetization, so the electric magnet has to induce in the studied material a magnetization level greater than about 0.8 T.



c *d*

Figure 2. Dependencies of the B_x component of the magnetization vector along the *OZ* axis for the U-type electromagnet on the thickness *d* of the sample (*a*), its width *w* (*b*), thickness of the air gap *g* (*c*), and the magnetizing current *I* (*d*): at 1 mm depth – graph *1*; at 4 mm depth – graph *2*; in the core of electromagnet – graph *3*

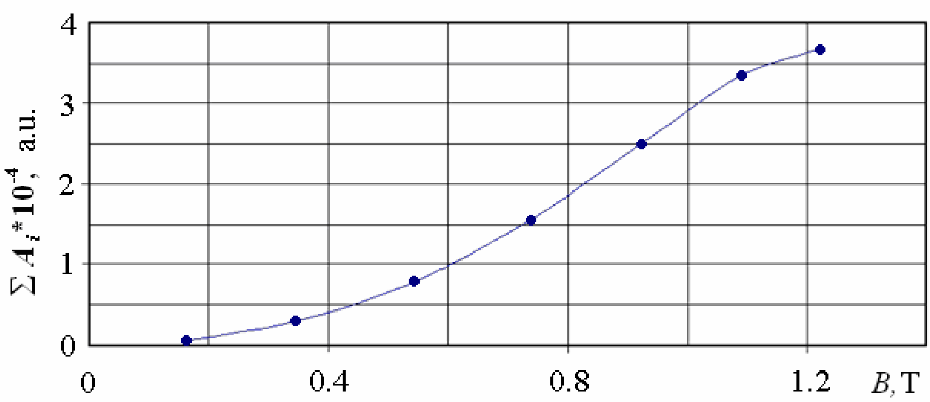


Figure 3. Dependence of the total sum of amplitudes of the MAE signal impulses on the amplitude value of magnetization in the plate

The further calculations have been done for the thicknesses of samples $d \leq 15$ mm. Numerical modeling of magnetization by a U-type magnet in the plates of such thicknesses incorporated variations in geometric parameters of the core, specifically the heights of the legs, the spacing between the poles, and the cross section of the core. The obtained results clarified that the magnetization level in the sample has very little dependency on the legs' height and on the spacing between the poles, but strongly depends on the cross-section of the core. An increase in the cross-section of the core of electromagnet leads to enhancement of magnetization of the sample, as far as the value and the depth is concerned.

A series of numerical simulations have been conducted for the different types of the core material. Employing the previous results and considering the availability of stock materials, we selected the core's cross-section 26x45 mm, distance between the poles 40 mm, and the leg's height 50 mm (as in more details outlined in [15], made of the electric cold rolled anisotropic sheet steel type 3406. Two windings were made of copper wire 0.63 mm in diameter with 1260 turns in each winding.

For the designed electromagnet we numerically modeled magnetic field induced in the 15 mm thick plate made of carbon steel grade 30. An axial section of the field distribution presented in Figure 4 illustrates that the volume under the electric magnet is magnetized to a sufficient level throughout the thickness of the plate.

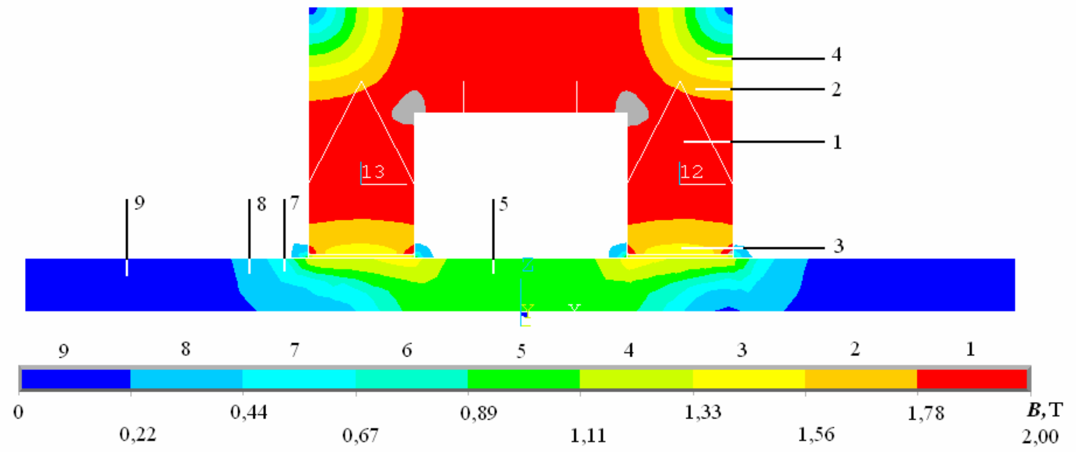


Figure 4. Longitudinal section of the distribution of the amplitude of magnetization in the plate

Engineering of the system for acquisition, processing and logging of MAE signals. In order to sense, process and record the MAE signals induced by the U-shaped electric magnet engineered as described above, the PC-controlled system called MAE-1L has been engineered also. Its block diagram is illustrated in Figure 5.

The MAE-1L system, which in more details is described elsewhere [15], contains an acoustic emission measuring channel that contain piezoelectric transducer connected with the input *1* of a preamplifier *2*, a band filter *3*, an amplifier with a program-controlled amplification *4*. The system contains also the following modules: analog-to-digital converter *5*, random-access memory *6*, digital-to-analog converter *7*, module for signal discrimination and analysis *8*, central processing unit *9*. The magnetic field control part is comprised of a generator *10*, a current amplifier *11* with two outputs *12* and *13*, and current measuring unit *14*. There is a battery power supply *15* and an optional input for external synchronization *16*. The system is connected with a personal computer via the interface *17*.

The work of this system is operated by the central processing unit *9*. The main parameters of the system are preset using a special program from a personal computer so that appropriate information is placed into the unit *9*. Depending on the operator's choice, the system can function in two different modes: asynchronous and synchronous. Asynchronous mode is convenient for research studies in the fields of applied physics and fracture mechanics when the acoustic emission impulses are randomly distributed in time [15]. The system starts recording the signal if the output of the amplifier *4* exceeds the preset discrimination level of the background noise.

A synchronous mode of operation is used for MAE studies when the MAE signal recording has to be synchronized with the phase of a magnetizing field so that the parameters of the recorded MAE signals (that are phase dependent) could be compared. The heart of the system is a Texas Instruments made microcontroller MSP430F2619T.

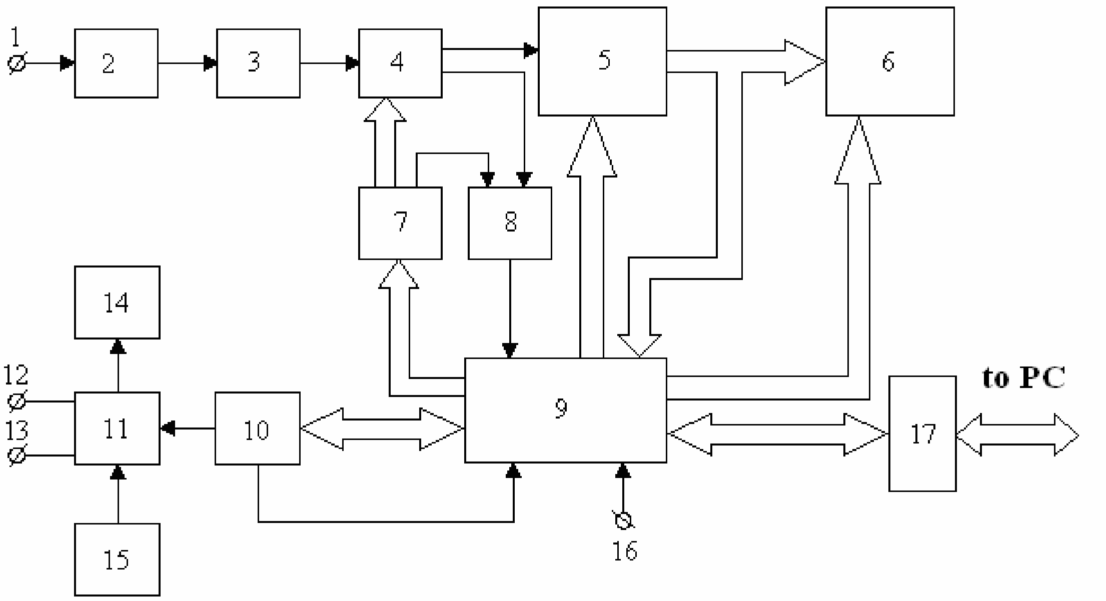


Figure 5. Block diagram of a PC-operated system for acquisition, processing and logging of MAE signals

For the operation of the designed MAE system a software package was developed. It allows the operator to select the modes of operation with subsequent planning of the experiment for the successful acquisition, processing and logging of MAE signals. Every recorded signal receives its unique file name and the parameters are being preset, such as the amplification coefficients, discrimination level, sampling frequency, sample length, frequency and amplitude of electromagnet power generator. During the experiment the signal is graphically presented in real time at the PC monitor together with the number of the sample and major parameters of data logging system. There has been developed software for post measurement analysis of the recorded MAE data.

The engineered MAE system has been successfully employed for studying the effects of plastic deformation and hydrogen absorption on low carbon steel, which results are presented at this conference in separate reports.

Conclusions. This paper describes the instrumentation that has been developed for MAE diagnostics of ferromagnetic materials that would open the possibility to research into the processes of degradation of structural materials in a non-destructive way. The complex of the MAE measuring system comprises of two parts: magnetic and acoustic. The reversible magnetic field is induced in the ferromagnetic material by the U-shaped electric magnet engineered by optimization using the numerical computer modeling and experimental measurements. The process of magnetization is accompanied with emission of elastic waves in the bulk of the material. These waves travel to the surface of the tested object causing the displacement of the surface, which is converted by the acoustic emission transducers, amplified and fed into the MAE measuring system which is responsible for acquisition, processing and logging of MAE signals. Such system named MAE-1L together with a software package has been engineered and its principal description is shortly outlined here.

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