System MAE-1L for Magnetoacoustic Emission Diagnostics of Structural Materials

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Abstract

The measuring system MAE-1L was engineered at Karpenko Physical-Mechanical Institute of the Ukrainian National Academy of Sciences. Development stages in engineering of a measuring system purposed for non-destructive evaluation of ferromagnetic structural materials that employs the phenomenon of magnetoacoustic emission (MAE) has been outlined. 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 together with the principles of a PC-operated measuring system designed for MAE signals acquisition, processing and logging. MAE system could be used in establishing the correlations between the MAE signal parameters and the parameters of the material, thus allowing an evaluation of the physical condition of structures and equipment made of ferromagnetic materials. The preliminary study are encouraging in foreseeing this type of nondestructive instrumentation to be used for evaluation of materials degradation and detection of in-service conditions that might stimulate accelerated aging of ferromagnetic structural materials.

Introduction

There is a growing need for the technical diagnostics of the aged 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 deformation 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 limitations 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, so there are attempts to employ only a single parameter like coercive force or residual magnetization with examples being the systems based on magnetic memory [2, 3].
Much more promising seems the method of magnetoelastic acoustic emission, also known as magnetoacoustic emission (MAE) that is based on the effect of generation of acoustic 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 to its surface 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. As of today, however, the MAE method 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 MAE measuring system, which could be employed in establishing the correlations 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 (often of a piezoceramic type) 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 overload of the 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 a magnetic field induced by a U-type electric magnet and by the solenoid (I-type electric magnet) [14]. It has been established that for the U-type the magnetized volume is better localized and propagates deeper (Fig. 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.

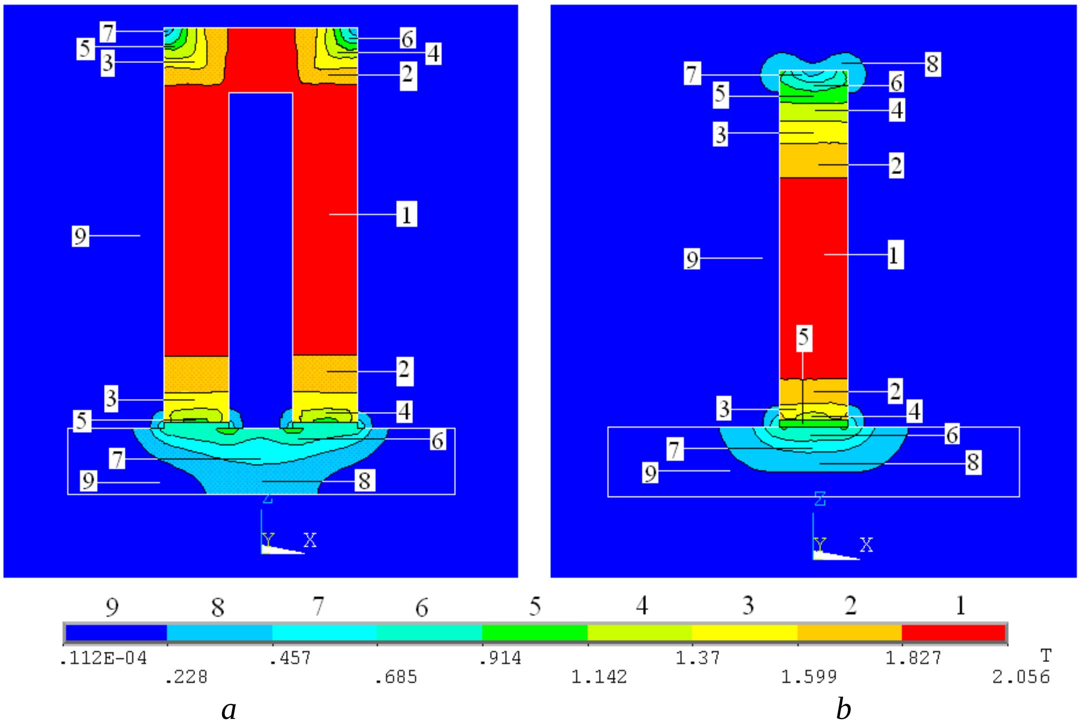

Fig. 1. Distribution of the magnitude of the magnetization vector in the plane *XOZ*: *a* – for the U-type electromagnet and *b* – for the I-type electromagnet.

Additional studies have been conducted regarding the distribution of the magnetic field in the case of a U-type magnet. Fig. 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 (Fig. 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 Fig. 2d it could be deduced that due to the nonlinearity of the dependency $B_x(I)$, 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.

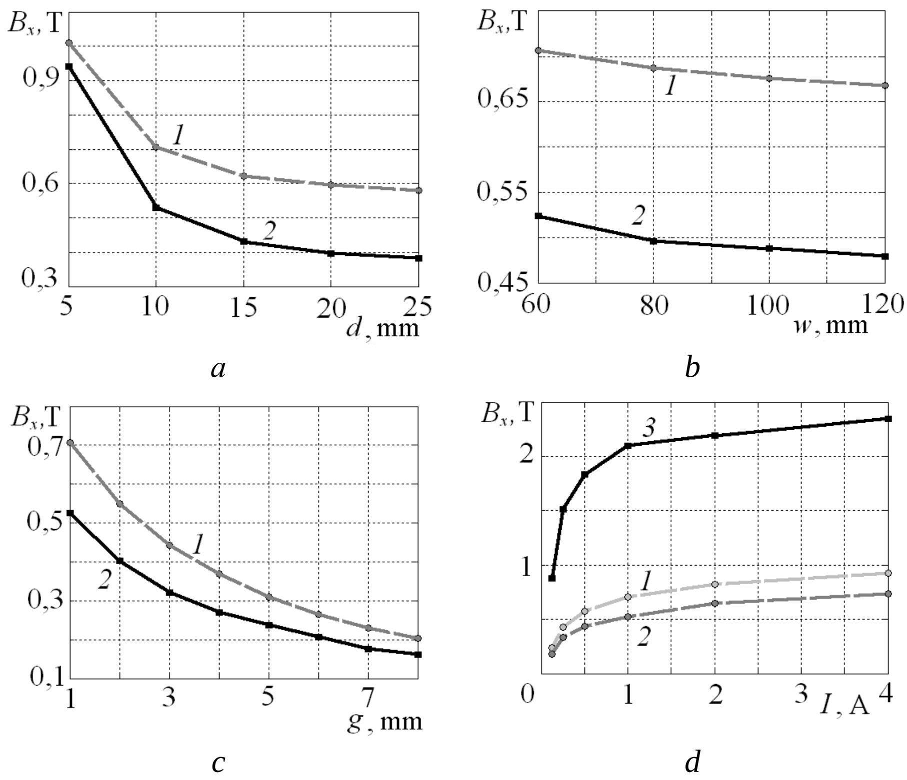

Fig. 2. Dependencies of the B_x component of the magnetization vector along the *OZ* axis for the U-type electromagnet on the thickness *d* of the sample (*a*), its width *w* (*b*), thickness of the air gap *g* (*c*), and the magnetizing current *I* (*d*): at 1 mm depth – graph *1*; at 4 mm depth – graph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

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 strip 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]. Fig. 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.

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.

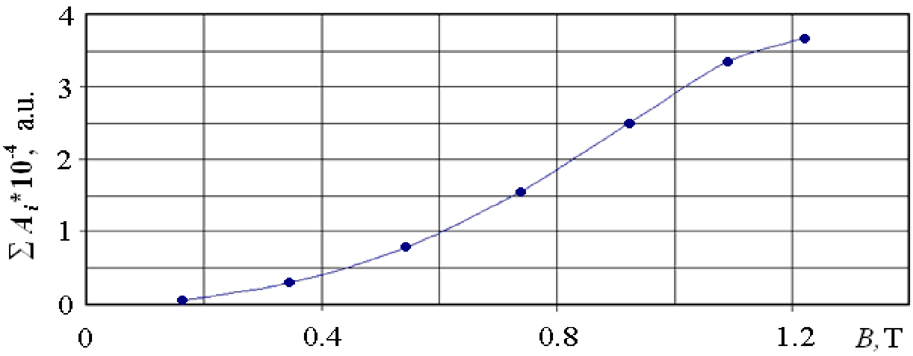

Fig. 3. The effect of the amplitude value of magnetization in the plate/strip on the total sum of amplitudes of the MAE signal impulses.

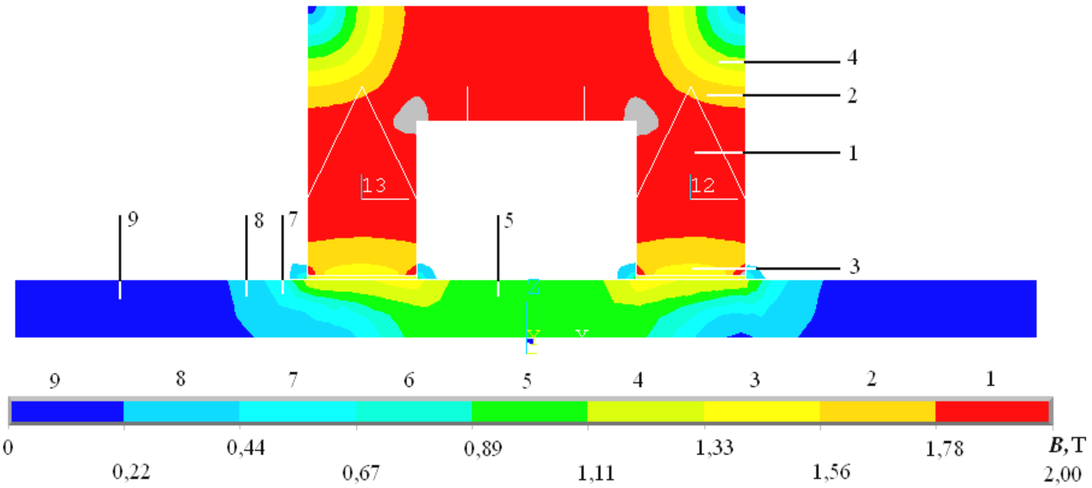

Fig. 4. Longitudinal section of the plate and the core of electromagnet with distribution of the amplitude of magnetization in ferromagnetic materials.

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 (analog to AISI 1030). An axial section of the field distribution presented in Fig. 4 illustrates that the volume under the electric magnet is magnetized to a sufficient level throughout the thickness of the plate. Please note that the degree of magnetization of the U-shaped core is twice as high as the maximum magnetization of the metal underneath.

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 Fig. 5. The MAE-1L system (technical details are more deeply described elsewhere [15]) contains an acoustic emission measuring channel that contains 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.

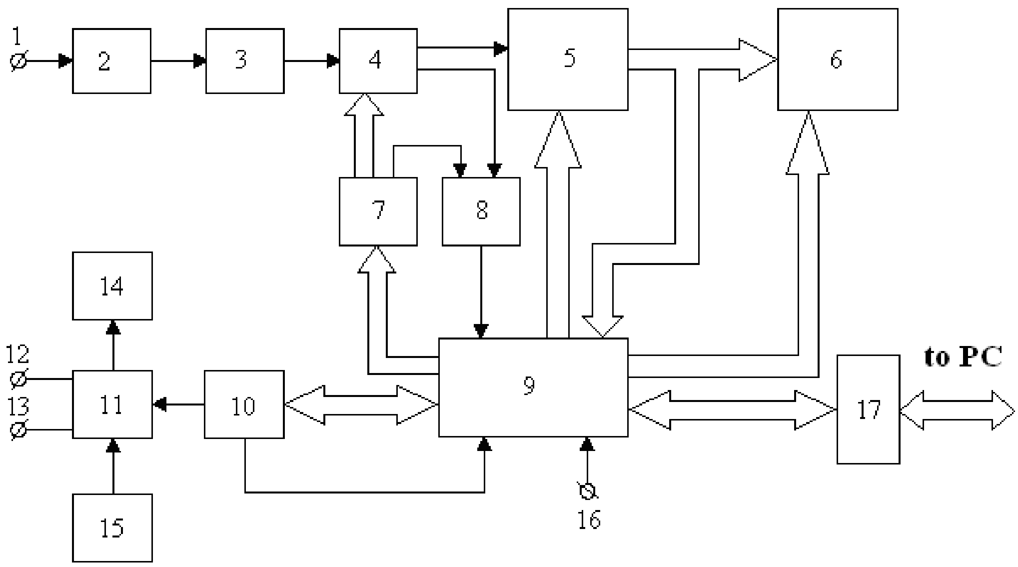

Fig. 5. Block diagram of a PC-operated system for acquisition, processing and logging of MAE signals.

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. Besides, there has been developed software for post measurement analysis of the recorded MAE data. Fig. 6 depics a photograph of the engineered MAE system together with electromagnet. This system has been successfully employed for studying the effects of deformation and of hydrogenation of low carbon steel. The results of these studies are presented at this conference in separate reports.

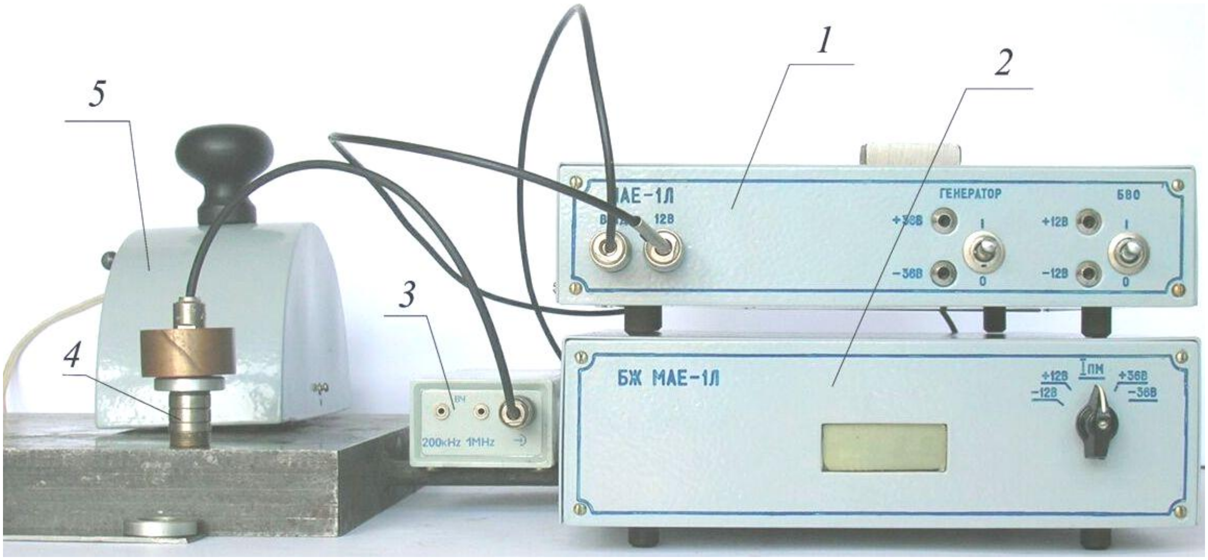

Fig. 6. A photograph of the system MAE-1L: *1* – the main unit, *2* – battery power unit, *3* – preamplifier, *4* – piezoceramic transducer, *5* – electromagnet.

Conclusions

The instrumentation that uses the phenomenon of magnetoacoustic emission has been developed for diagnostics of ferromagnetic materials opening the possibility for studying the processes of structural materials degradation in a non-destructive way. Development stages in engineering of a measuring system has been outlined. 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 together with the principles of a PC-operated measuring system designed for MAE signals acquisition, processing and logging. MAE system could be used in establishing the correlations between the MAE signal parameters and the parameters of the material, thus allowing an evaluation of the physical condition of structures and equipment made of ferromagnetic materials. The preliminary study are encouraging in foreseeing this type of nondestructive instrumentation to be used for evaluation of materials degradation and detection of in-service conditions that might stimulate accelerated aging of ferromagnetic structural materials.

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