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ELECTROMAGNETIC METHODS

Automated System for Complex Non-Destructive Testing of the Structure and Mechanical Properties of Mechanical Engineering Materials

Boris Georgiev Velev[a], **, Ivan Stoyanov Ivanov[b], and Vladimir Vasilev Kamenov[c], *

[a] *Institute of Mechanics—BAS, Sofia, 1000 Bulgaria*

[b] *University of National and World Economy, Sofia, 1000 Bulgaria*

[c] *Department of Mechanical Engineering, Technical University—Sofia, Sofia, 1000 Bulgaria*

**e-mail: vladokamenov@gmail.com*

***e-mail: boris_velev81@abv.bg*

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Abstract—An automated system with two optimized modular devices is presented—MULTITEST-MC010 for research of ferromagnetic materials with the methods for measuring magnetic noise and magneto acoustic emission of Barkhausen and MULTITEST—CD010 for research of mechanical engineering materials with the methods of velocity measurement of longitudinal waves C and attenuation coefficient δ of ultrasound. The main approaches and principles for the automated data processing of complex non-destructive testing are presented, as well as the setup of the modular devices of the automated system. For approbation of the system the influence of the heat treatment (hardness) in structural steel 40X on the non-destructive information parameters of the magnetic noise and the magneto acoustic emission—magnetic noise voltage E_{BN} and voltage of the magneto acoustic emission E_{MAE} was studied. The mechanical properties in foundry cast iron samples with complex measurement of the information parameters E_{BN}, E_{MAE} C, by simultaneous use of the two modular devices of the system were also studied. The possibility for the complex application of these parameters for non-destructive testing of the mechanical properties after heat treatment in structural steel 40X and the tensile strength in cast iron specimens has been proven.

Keywords: complex non-destructive testing, non-destructive information parameters

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INTRODUCTION

With the increased requirements to the quality and reliability of mechanical engineering materials and equipment, there is a need for research, development and introduction in the industry of complex systems for non-destructive testing of mechanical properties, mechanical internal stress and structure of materials [5, 6, 8, 10]. The complex research and evaluation of the properties of materials and products can be performed by the simultaneous use of several non-destructive methods, which combines and mutually complements their capabilities [8, 9, 11, 12]. For the application of automated complex non-destructive testing it is necessary to use the methods of statistical analysis and modern software products [1]. For this purpose, a modular automated system MULTITEST has been developed for non-destructive testing and research of the structure, composition and mechanical properties of materials in laboratory and industrial conditions [8]. It is based on the complex use of several physical methods (magnetic, acoustic and electrical), each of which can be used independently [2–5, 8].

1. PURPOSE

The aim of this paper is to present the basic principles and algorithms for automated evaluation of data from complex non-destructive testing with the help of the modular devices of an automated system, consisting of modular device for magneto-noise and magneto-acoustic examination of ferromagnetic materials MULTITEST-MC010 and with modular device MULTITEST-CD010 for complex testing of mechanical engineering materials with the methods for measuring the speed and attenuation of ultrasound [4, 8, 9].

In order to test the system, the other purpose of this article is to conduct research and develop methods for complex non-destructive testing of samples of structural steel and cast iron, as well as to analyze the results and conclusions on the applicability of complex non-destructive testing.

2. BASIC PRINCIPLES OF COMPLEX NON-DESTRUCTIVE TESTING

The basic principle of complex non-destructive testing is that the practical expediency of increasing the non-destructive information parameters is determined by the probability of correct assessment of the properties of controlled samples or materials classified by one information parameter and compared with the probability of correct assessment of materials classified by two or more information parameters. It is logical that when insufficient information is obtained about the controlled material when applying only one method, the use of a properly selected second method will increase the likelihood of a correct assessment of the properties of the material [7, 8]. To assess this probability, non-destructive testing data are subjected to statistical processing [1].

2.1. Automated System for Data Processing and for Measuring/Testing in Complex Nondestructive Testing

The development of software for automated data processing and evaluation, and software for automated measurement/testing of the system is the first step towards the development of methodologies for complex non-destructive testing and covers the following stages:

— Calculation of average values and interval estimates of the series of measurements, performed on one, two or more non-destructive information parameters:

(a) One-parameter interval estimation.

(b) Multi-parameter interval estimation.

— Classification criteria.

(a) Pre-training system through comparative samples.

(b) Self-learning systems.

— Software for automated data processing for classification of samples and details by groups with identical properties.

— Software for the measurement/test system.

2.1.1. Algorithms for automated data processing and classification of samples and parts into groups with the same mechanical properties or structure

— One-parameter interval estimation.

If we have n measurements on the controlled material of one non-destructive information parameter $\{x_i;\ i = 1, \dots n\}$, the estimate in this case will be:

$$\bar{x} = \frac{i}{n}\sum_{i=1}^{n} x_i, \tag{1}$$

and the interval estimate at probability P will be:

$$\bar{x} \pm c(P_r)s, \tag{2}$$

where s is the standard deviation is:

$$s = \left[\frac{1}{n-1}\left(\sum x_i^2 - \frac{1}{n}\left(\sum x_i\right)^2\right)\right]^{\frac{1}{2}}, \tag{3}$$

where $c(P_r)$ is the correction factor taking into account the small sample size is:

$$c(P_r) = \frac{1}{\sqrt{n}}(t_{q,v});\ n-1, \tag{4}$$

where $t_{q,v}$ is a quantile of the Student's distribution; $q = \dfrac{1+P_r}{2}$; $v = n - 1$.

The values of $t_{q,v}$, q and v can be approximated with sufficient accuracy for practice:

$$t_{q,v} = \lambda_q + \sum_{i=1}^{4} \frac{q_i^{(\lambda_q)}}{v^i}, \text{ where } \lambda_q = r - \frac{\left(\sum_{k=0}^{2} c_k r^k\right)}{\left(\sum_{k=0}^{3} d_k r^k\right)}; \quad r = \sqrt{l_n \frac{1}{q^2}}. \tag{5}$$

The values of the coefficients in (5) are:

$c_0 = 2.30753$; $d_0 = 1$; $c_1 = 0.27061$; $d_1 = 0.99229$; $c_2 = 0$; $d_2 = 0.04481$; $d_3 = 0$.

The approximation makes it possible to determine the quantiles $t_{q,v}$ and, respectively, the interval estimates for the number of measurements n and probability P_r.

Multi-parameter interval estimation

If we have measurements $x_{ij}^{(k)}$ where $1 \le i \le n_k$; $1 \le j \le \rho$; $1 \le k \le m$; ρ—number of parameters; n_k—number of measurements on the kth sample; m—number of samples. The point evaluation in this case is:

$$\overline{x}_j^{(k)} = \frac{1}{n} \sum_{i=1}^{n_k} x_{ij}^{(k)}, \tag{6}$$

and the interval assessment will be:

$$\overline{x}_j^{(k)} \pm c(P_r) s_j^{(k)} \quad j = 1 \ldots \rho, \quad k = 1 \ldots m, \tag{7}$$

where $c(P_r)$ is correction factor:

$$c(P_r) = \left[\frac{(n_k - 1)\rho}{(n_k - \rho) n_k} Fqi_{k-2}^{n} \right]^{1/2}. \tag{8}$$

To approximate the t-distribution, the approximation (5) can be taken. In the interval estimation (7) the standard deviation is denoted by $S_f^{(k)}$ and is determined by the expression:

$$S_f^{(k)} = \left[\frac{1^{n_k}}{n_{k-1}} \sum_{i=1} \left(x_{ij}^{(k)} - \overline{x}_{ij}^{(k)} \right)^2 \right]^{1/2}. \tag{9}$$

For example, if we have three parameters $j = 1, 2, 3$, then the 3σ interval for the jth parameter of the $\hat{e}$th group of samples is determined by the expression:

$$v_{(r)}^{(j)} = m_k^{(j)} + 3\sigma_k^{(j)}; \quad v_{(\Delta)}^{(j)} = m_k^{(j)} + 3\sigma_k^{(j)}; \quad k = 1, 2, 3, \tag{10}$$

$v_{(r)}^{(j)}$ is the upper limit value; $v_{(\Delta)}^{(j)}$ is the lower limit value.

— Classification criteria.

The analysis of the theoretical prerequisites shows that the following recognition systems can be applied in the formation of criteria:

(a) Prior learning system using comparative models.

They form characteristic areas through confidence intervals with a certain degree of probability. Such a system is the multi-parameter analysis of variance, the single-parameter and multi-parameter interval estimates presented above. After calculating the confidence intervals, it is proceeded to the classification of unknown samples or details to the respective groups of comparative samples. The average of several independent measurements is used as a criterion. Practically in this system two to five independent measurements of each information nondestructive parameter on the material are performed, the average value of the measurements is calculated and if it is within the confidence interval $\overline{x} \pm 3\sigma$, then the material (part) belongs to the respective group. Another data processing system is the use of robust (sustainable) interval estimates [1].

(b) Self-learning systems.

When classifying a relatively small number of samples or details, the data sets are not large. In this case, it is not appropriate to apply the probabilistic approach with comparative samples. Data analysis methods based on the similarity between the individual measurements are more appropriate. Such a self-learning system is cluster analysis [1]. Cluster analysis is particularly suitable for high-scatter measurements, such as many non-destructive testing methods.

2.1.2. Measurement/testing algorithms for automated complex non-destructive testing. For each modular device, the tuning and calibration algorithm is independent [6, 7]. In order to establish the correlations between the non-destructive information parameters, the structure and the mechanical properties of the controlled materials, as well as to form a classification criterion, algorithms have been developed in the following sequence:

— Algorithm for modular device MULTITEST-MC010.

(a) Comparative samples of the controlled test material shall be selected with the following information:

— type of test material, brand, production technology, hardness, mechanical and physical properties and others. They are used to construct the $E_{\rm BN} = F(I_{\rm B}, f)$ and $E_{\rm MAE} = F(I_{\rm B}, f)$. The obtained dependences are approximated with functions of the form:

$$E_{\rm BN} = (a_k f_{\rm B}^2 + b_k f_{\rm B} + c_k)^{-1}, \quad (11)$$

$$E_{\rm BN} = a_k \exp\{b_k[\exp(c_k I_{\rm B})]\}, \quad (12)$$

where $I_{\rm B}$ is the magnitude of the magnetizing current, f is the frequency of the magnetic noise; $E_{\rm NB}$ is the magnetic noise voltage; $E_{\rm MAE}$ is the voltage of the magneto acoustic emission. Dependences (11) are approximated to the quadratic equation:

$$f_{\rm B}^2 + af + c = 0, \quad (13)$$

whose roots represent the optimal frequency of the magnetic noise $f_{\rm onm}$ and on the basis of this frequency the dependences $E_{\rm BN} = F(I_{\rm B})$ are obtained. These dependences (12) are approximated by the nonlinear equation:

$$\exp[\varphi_l(I_B^{(1)})] = A\exp[\varphi_l(I_B^{(2)})] = 0. \quad (14)$$

(b) From Eq. (14) the maximum range between the values of the approximated data is found and from them the optimal value of the magnetizing current $I_{\rm Bopt}$ is determined. Real samples with unknown structural and mechanical characteristics are measured at this current. A similar procedure is performed to optimize the measurements of the magneto-acoustic emission, through the dependences $E_{\rm MAE} = F(I_{\rm B}, f)$, in order to find the optimal frequency and the optimal magnetizing current of the magneto-acoustic voltage $E_{\rm MAE}$, at which measurements of real samples with unknown structure or mechanical properties are made.

— Algorithm for modular device MULTITEST-CD010.

This device uses a method for measuring the speed and attenuation of ultrasound in solid materials with a single measurement, which simultaneously determines the actual thickness of the controlled material and the distance travelled by the ultrasound in it [3]. Both values are processed and the speed or attenuation of the ultrasound in the material is indicated on a digital indicator [4]. The main steps for setting up and calibrating the MULTITEST-CD010 are as follows:

(a) The setting of the working range is determined, according to the instruction of the device, to the minimum and maximum thickness of the controlled material so that the range of the actual thicknesses of the material fits into the working range. For this purpose, two consecutive measurements are made on two sections (with minimum and maximum thickness) of the РКБ standard [7] and are adjusted so that:

$$d_{ye1} = d_{oe1} = d_{e1} \text{ and } d_{ye2} = d_{oe2} = d_{e2}, \quad (15)$$

where d_{e1}, d_{e2} are the actual thickness of the measured two sections of the standard [7]; d_{oe1}, d_{oe2} are the thickness of the same two sections, measured with an optoelectronic sensor; d_{ye1}, d_{ye2} are the relative thickness of the same two sections, measured by ultrasound. The following formula is used to calculate the speed of ultrasound:

$$C = k(d_y/d_o)C_e. \quad (16)$$

(b) For the attenuation coefficient at a given frequency δ_t, the following formula is used:

$$\delta_t = \frac{(A_1 - A_n) - B}{2d_o(n_1 - n_n)}, \quad (17)$$

where C_e (m/s) is the speed of ultrasound in the standard of Armco iron [3, 7]; k is the coefficient of proportionality, taking into account the external conditions; d_y (mm) is the relative thickness of the material,

Fig. 1. Appearance of the system with configuration—test pliers DK100 and devices MULTITEST-MC010 and MULTITEST-CD010.

measured by ultrasound; d_o (mm) is the actual thickness measured with an optoelectronic sensor; δ_t (dB/mm) is the attenuation coefficient at frequency t; n_1 and n_2 are the number of the compared echo pulses; A_1, A_n are the amplitudes of the compared ultrasonic echo pulses.

In the present study, the non-destructive information parameter—the longitudinal velocity of ultrasound C for simplicity is presented as a dimensionless ratio M of the velocities in the controlled material and in the standard of Armco iron. For $k = 1$ of formula (16) it follows that $M = C/C_e = d_y/d_e$. The ratio M allows only by measuring the thicknesses, without calculating the speed of the ultrasound, to register with sufficient accuracy for the practice the change of the speed of the ultrasound in the different materials. This parameter is selected as an additional one and is measured according to the measurement/test program and the calibration methodology [4].

2.1.3. Software. For the automated system for complex non-destructive testing, software for collection, analysis and evaluation of experimental data, as well as software for measurement/testing for each of the modular devices have been developed, according to the algorithms described in detail above [7, 8]. The software uses software systems—MatLab for data evaluation and measurement/testing of system components and the graphical program LabVIEW for online visualization of results.

The non-destructive information parameters were tested—magnetic noise voltage E_{BN}, magneto acoustic voltage E_{MAE} and ratio of ultrasonic speeds M in samples and details of mechanical engineering materials. The system is tested with data obtained from the MULTITEST-MC010 and MULTITEST-C010 modular devices. The measurements are performed on comparative samples of structural steel 40X and cast iron.

3. EQUIPMENT, MATERIALS AND RESEARCH METHODOLOGY

3.1. Equipment

The automated system MULTITEST consists of 3 parts—personal computer for automatic data processing and evaluation, as well as classification of measured samples, modular instruments for measuring non-destructive information parameters and devices (measuring pliers, manipulators, etc.) for gripping and moving. The modular devices are self-powered and can work independently or in a single automated system, depending on the tasks. Figure 1 shows a picture of the system configuration with the MULTITEST-MC010, MULTITEST-CD010 modular devices and the DK100 measuring pliers.

3.2. Materials

In order to establish correlations between the non-destructive information characteristics, the structure and the mechanical properties of the controlled materials, it is necessary to prepare comparative samples. To test the system, comparative samples of structural steel 40X (according to GOST 4543-71) and cast iron (gray cast iron according to GOST 1412-85 and high-strength cast iron according to GOST 7293-85) were selected. The samples of steel and cast iron are in the form of rectangular parallelepipeds with dimensions $\Phi30 \times 20$ mm. The 40X steel specimens have different degrees of heat treatment performed in an inert CO_2 environment, 5 pieces in each group. The comparative specimens of foundry gray and high-strength cast irons are also 5 pieces in each group and have different tensile strength.

Table 1. Mechanical properties of the groups of comparative samples

Groups of steel samples 40X		Groups of samples of cast iron: high-strength cast iron and gray cast iron		
no.	HB hardness	no.	tensile strength *Rm*, MPa	
1	380–410	1	120–157	СЧ15
2	360–390	2	300–337	СЧ30
3	330–365	3	450–500	ВЧ50
4	300–310	4	590–630	ВЧ-60
5	–	5	640–675	ВЧ60-2

The affiliation of the comparative samples to the respective group with the same mechanical properties was confirmed by chemical and metallographic analysis and mechanical testing of hardness and tensile strength.

The type of heat treatment and the Brinell hardness data for the 40X steel specimens and the tensile strength in the cast iron specimens are given in Table 1.

3.3. Methodology for complex non-destructive testing

For approbation of the device and the system for data processing and evaluation, a specific methodology has been developed for non-destructive testing of the hardness (heat treatment) of 40X structural steel samples and the tensile strength of cast iron samples:

• Object of complex non-destructive testing:

— Object of control are samples and details of structural steel 40X and cast iron with dimensions Φ30 × 20 mm.

• Equipment and fixtures:

— Devices MULTITEST-MC 010, MULTITEST-CD010;

— Accessories—DK100 test pliers. For the application of complex non-destructive testing with magnetic noise and ultrasonic methods, specially designed test pliers DK100 are used for calibration and measurement (Fig. 1);

— Personal computer (laptop);

— Magnetic-noise transducers and ultrasonic piezoelectric transducers;

— Series of comparative samples with different heat treatment and tensile strength (Table 1);

— Necessary documentation and software to the system (Operating instructions, Database, Methods for calibration and testing, etc.).

• Preparation of comparative samples:

— In each group 5 samples with identical properties were selected (Table 1);

— The preparation includes consecutively the following operations—lathe machining, labelling and pre-setting and selection of samples. The selected samples are subjected to heat treatment, cleaning with a sandblasting machine, chemical analysis with a quant meter, determination of average hardness by HB from 3 independent measurements;

• Measurement of the non-destructive information parameters of the samples, according to the developed software programs and the above-stated algorithms for formation of characteristic areas, as well as through the software for measurement/testing in complex non-destructive testing [8];

— In this case only part of the algorithm presented in Ch. 2.1.2 is used—only the dependences of the non-destructive information parameters on the magnetizing current $E_{BN} = F(I_B)$ and $E_{MAE} = F(I_B)$ of formula (14). The frequency of the magnetic noise f_{BN} is measured in the general frequency range (1–100) KHz, and the frequency of the magnetic noise emission f_{MAE}—(10–200) KHz;

— For the third additional non-destructive information parameter, the longitudinal velocity of the ultrasound C of formula (16) is determined, which for simplicity is presented as a dimensionless ratio M of the velocities in the controlled material and in the standard [4];

— Defining classification criteria. In E_{VN} and E_{MAE}, which are the main information parameters, the maximum distance of the families of curves from the comparative samples serves as a criterion (Fig. 2). From them the optimal operating current I_{opt} is determined, the characteristic areas are determined too (Fig. 3). When using the information parameter M, three-parameter characteristic areas are formed (Fig. 5);

— Graphic visualization and memorization of characteristic areas.

• Preparation for complex non-destructive testing of real details:

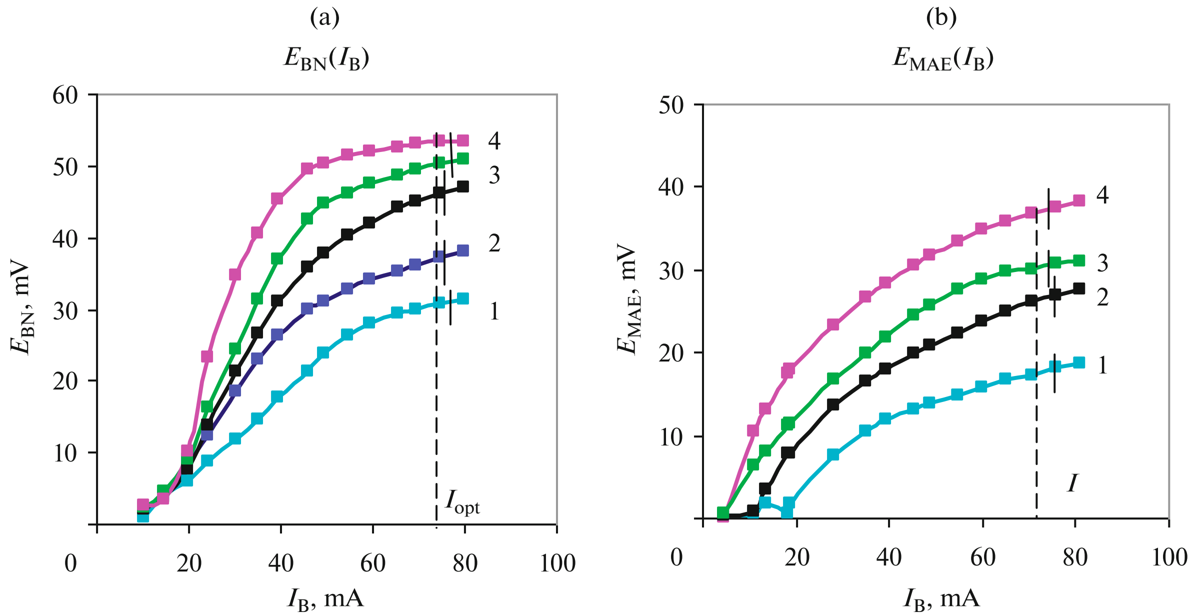

Fig. 2. One-parameter confidence intervals of the $E_{BN}(I_B)$ and $E_{MAE}(I_B)$ series of curves of the groups of comparative samples of 40X steel.

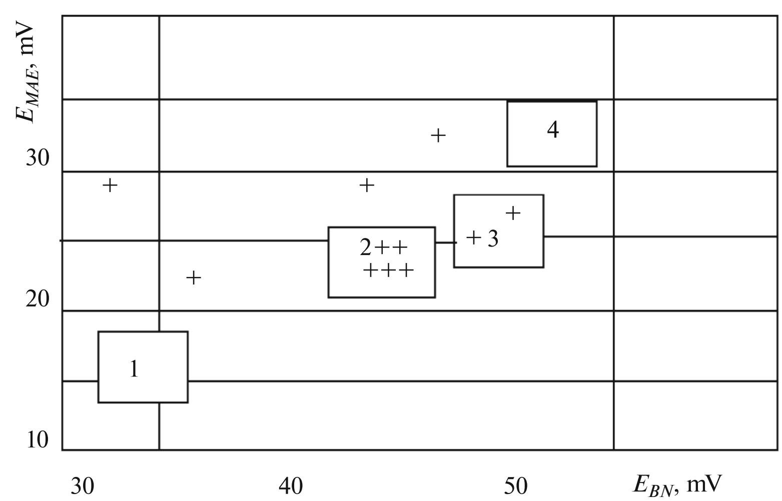

Fig. 3. Characteristic areas of 40X steel specimens. Information parameters: E_{BN} and E_{MAE}.

After determining the characteristic areas and the criterion for classification from the groups of comparative samples, the measurement of real details is started. Preparation for measurement includes:

— Determining the conformity of the batch and the brand of the production details, subject to control and their conformity with the brand of the comparative samples;

— Cleaning the details with a sandblasting machine.

• Method of measurement.

— For measuring E_{VN} and E_{MAE}, the controlled part, by the device DK100, shown in Fig. 1, is pressed against the magnetic-noise transducer and the piezoelectric transducer with a constant force *P*. The same device DK100 [7] is used to measure *M*;

— Non-destructive information parameters are determined on the basis of 3 to 5 independent measurements of each controllable part. Controllable parts are classified into groups with the same mechanical properties (hardness or tensile strength) with a certain degree of probability.

• Printing the results in a protocol:

For each specific case, a similar methodology is made for another material or product.

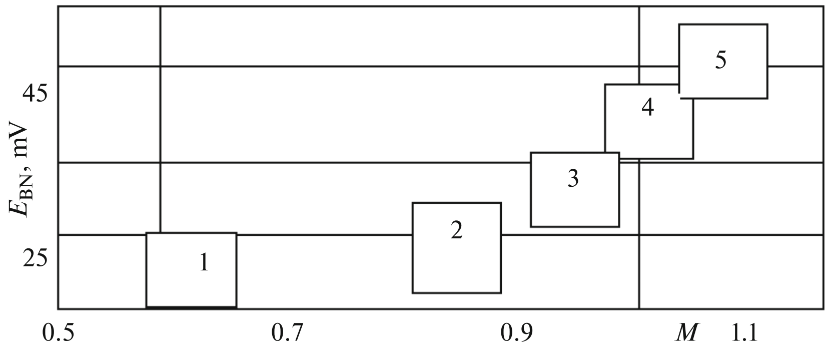

Fig. 4. Characteristic areas in two-parameter non-destructive testing of cast iron. Information parameters: E_{BN} and M.

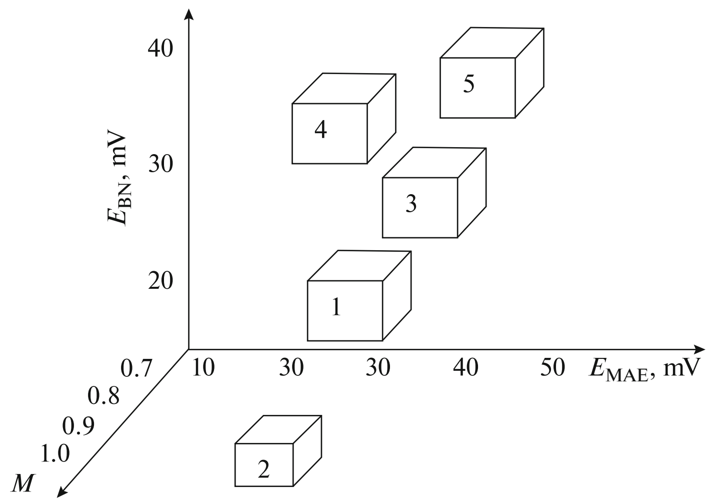

Fig. 5. Characteristic areas in three-parameter non-destructive testing of cast irons Information parameters, M, E_{BN} and M_{AE}.

4. EXPERIMENTAL RESULTS

According to the methodology of 3.3, the prepared comparative samples made from 40X steel are subjected to measurements according to the following procedure:

— The scanning of $E_{BN}(I_B)$ is performed at maximum magnetizing current and the optimal current I_{opt} = 75 mA is determined automatically by the curves in Fig. 2a;

— At the same time, the second non-destructive information parameter is scanned—magneto acoustic voltage $E_{MAE}(I_B)$ from the curves in Fig. 2b.

From Fig. 2 it can be seen that the value of the magnetizing current I_{opt} = 75 mA is sufficient for simultaneous measurement of both information parameters with the device DK100, shown in Fig. 1. The optimized parameter I_{opt} is stored in the device and k measurements are made with it for each comparative sample. The obtained data are stored in the memory of the instrument and the formulation of classification criteria can be started. Figure 3 shows the characteristic areas of the groups of standard samples of steel 40X, formed by the complex measurement of the nondestructive information parameters E_{BN} and E_{MAE}, and formed according to the above methodology.

The overlap of the characteristic areas is a criterion for indistinguishability of the groups of samples. Similar measurements were made on the comparative samples of foundry cast iron according to the methodology described above. The results are visualized in Figs. 4 and 5.

5. ANALYSIS OF EXPERIMENTAL RESULTS

From Fig. 2 it follows that when using only the information parameter E_{BN}, the one-parameter confidence intervals of groups 3 and 4 will overlap, therefore they are difficult to distinguish, and when using only the information parameter E_{MAE}, the confidence intervals of groups 2 and 3 overlap. In the complex use of the two information parameters, the characteristic areas do not overlap, as in Fig. 3, therefore the probability of correct classification of the controlled material by mechanical properties increases.

Depending on the characteristic areas formed by the comparative samples, the classification of real details or materials is started, according to the methodology. The average values from the measurement of real samples are marked with crosses. If we have selected group 2 for hardness comparable samples, then the real samples marked with crosses that are outside the characteristic area 2 do not have the required hardness.

A comparative analysis of the results of the non-destructive testing of the groups of samples of foundry cast irons was made (Table 1, right). Figure 4 presents the characteristic areas for complex use of two non-destructive information parameters E_{BN} and M. The overlap of the characteristic areas is an indicator of indistinguishability of the groups, therefore spherical graphite cast irons (groups 3, 4 and 5) are difficult to distinguish in terms of strength properties in the two-parameter non-destructive control.

Figure 5 shows the characteristic areas when conducting three-parameter non-destructive testing. The analysis shows that the three-parameter non-destructive testing achieves a confident division of the cast iron samples into groups with the same strength properties.

6. CONCLUSIONS

The developed automated system for complex measurement of the information nondestructive parameters—magnetic noise voltage E_{BN}, voltage of magneto acoustic emission E_{MAE} and speed of ultrasound C, can be used in non-destructive testing of heat treatment and strength properties of structural steel and cast iron specimens.

The algorithms presented in this paper allow for software development through the use of modern open source software systems—MatLab and LabVIEW, which are a prerequisite for reliable complex non-destructive testing of the mechanical properties of mechanical engineering materials.

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