TESTING OF AUTOMATICIZED SYSTEM FOR COMPLEX NON-DESTRUCTIVE STUDY OF METALLIC MATERIALS

Dzhudzhev B.[1] , Angelov V.[2] , Zlatkov M. [3], Kostadinov P.[3]
Technical University-Sofia[1] , Institute of Mechanics - BAS[2], Todor Kableshkov University of Technology[3]

Summary:

A program to test automatized system for complex non-destructive testing of the structure, the physical and mechanical properties of samples and products from metallic materials is presented. The system consists of several modular devices that measure two non-destructive information parameters based on methods with different physical principles (magnetic, acoustic, thermoelectric, etc.). In the paper only two modular units - MULTITEST MC010 for testing ferromagnetic materials, based on the measurement of the magnetic noise voltage and magnetoacoustic emission and MULTITEST CD010 for testing of metallic materials based on measuring the speed and the attenuation coefficient of ultrasonic waves in the materials are presented. General methodology of the testing / measuring system, as well as methodology for calibration and metrological assurance of the equipment in operation of the system in a complex non-destructive testing has been developed. Conclusions are made on the reliability of the system measurements when used in complex non-destructive control of metallic materials.

Keywords: COMPLEX NON-DESTRUCTIVE TESTING

1. Introduction

The methods of magnetic noise and magneto-acoustic emission based on the Barchausen effect are increasingly being used for non-destructive testing of the structure and physico-mechanical properties of ferromagnetic materials. Their non-destructive parameters are recorded while a low frequency magnetic field is applied on the ferromagnetic material to obtain objective, repetitive information [1, 2, 3, 5, 6]. The MULTITEST MC010 was developed on the basis of those methods to measure the numerical characteristics of magnetic noise and magneto-acoustic emission – the voltage of magnetic noise and the root mean square of magneto-acoustic emission. There is an ultrasound method used to measure the velocity and attenuation of ultrasound waves in materials. It is suitable for testing the structure and strength of materials by obtaining information from the volumetric ultrasound waves passing through the entire section of the material [4]. The MULTITEST CD010 was developed on the basis of that method to measure the velocity of longitudinal ultrasonic wave propagation and the ultrasonic attenuation coefficient in the test material. These modular devices can operate as standalone units or be integrated into an automated non-destructive testing system for metallic materials.

2. Aim of this paper

The main aim of this paper is: to create a general testing/measurement methodology, the structure and content of which should be followed in the development of specific non-destructive testing methods; to develop and analyze the conditions to be met by the types of benchmark and reference samples used for calibration and metrological assurance of the automated system for the modular devices presented herein; to test and analyze the system using groups of reference samples with known mechanical characteristics.

3. Main principles of complex non-destructive testing

A general principle of non-destructive testing is that the practical expediency of increasing the number of non-destructive parameters is determined by the probability of properly assessing the properties of test samples or materials classified by one parameter and compared to the probability of properly assessing materials classified by simultaneous measurement of two non-destructive parameters. It is logical that if insufficient information about the test material or product is obtained using only one testing method, the use of a suitably selected second method will increase the probability of making a proper assessment of the material's properties. To estimate this probability, non-destructive testing data is subjected to statistical processing. This covers the following stages:

3.1. Interval assessments

The mean values and interval assessments of the series of measurements performed by one or two non-destructive parameters are determined. Calculations for one or two of the following parameters are made:

(a) Single-parameter interval assessment (Fig. 3b).

(b) Two-parameter interval assessment (Fig. 4).

3.2. Classification criterion

A system of pre-training through reference samples is used. The samples form characteristic areas through confidence intervals with a certain degree of probability. Such a system represents the single-parameter and two-parameter interval assessments mentioned above. After the confidence intervals are calculated, unknown samples or parts are classified into the relevant groups of reference samples. The average of several independent measurements is used as a criterion. In practice, this system consists of the following steps: 2-5 independent measurements of each non-destructive parameter are simultaneously performed on the test material, the average of the measurements is calculated and if it is within the confidence interval $\bar{x} \pm 3\sigma$, the material (part) belongs to the relevant group.

3.3. Software

Software for collecting, analyzing and evaluating experimental data obtained from the measurement of non-destructive parameters of samples and products made of metal materials has been developed. MatLab was used for evaluation and LabVIEW was used to display the results.

4. Testing equipment and methods

4.1. Testing equipment

Fig. 1. System of DK100 testing jaws and MULTITEST MC010 and MULTITEST CD010 devices

Fig. 1 shows the two modular devices and the apparatus (measuring jaws) used to conduct comprehensive non-destructive testing. Each device can independently measure two non-destructive parameters. The novelty in this automated system is that two non-destructive parameters with a different physical principles (for example, combination of a magnetic parameter and an acoustic one or of an electrical parameter and an ultrasound one, etc.) can be measured simultaneously, which increases the test's reliability. It is possible to measure other parameters with a different physical basis, e.g. thermoelectric, eddy-current, etc.

4.2. Measurement/testing method

It has been developed in accordance with EU standards on measurement certainty assessment [3] and contains the following sections:

- subject of measurement/testing;
- purpose of measurement/testing;
- general conditions;
- scope and procedure of measurement/testing;
- measurement/testing calibration methodology;
- conditions in which the testing is conducted;
- description of the method used to verify each parameter against the list of verifiable parameters from the "Scope of testing" section of the measurement/testing methodology;
- processing, analysis and assessment of the test results for each method for each verifiable parameter;
- reporting.

4.3. Methods for calibration of modular devices

- Subject of calibration. The subject of calibration is the MULTITEST MC010 and MULTITEST CD010 modular devices. They are designed as completely autonomous devices, so they can be used on their own. Their operation and measurement modes are described in detail in the Operating Instructions.
- Purpose of calibration. Calibrate the devices, so they are ready for testing.
- Type of calibration. The MULTITEST MC010 is calibrated with reference samples to ensure the results are reproducible. There are two types of sample – cylindrical with polished flat transverse surfaces for a contact transducer and cylindrical with a polished cylindrical surface for penetration. The MULTITEST CD010 is calibrated using the stepped reference sample shown in Fig. 2:

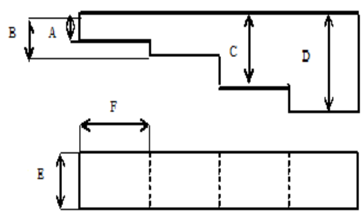


Fig. 2. Stepped reference sample calibration

- Main calibration characteristics. The reproducibility of the operation of the converter/modular device system must be verified using the reference samples made of Armco iron. For the MULTITEST MC010, it is possible to adjust the magnetization conditions in order to achieve reproducibility. The reproducibility is verified by statistical processing of previous data and the data obtained now and by assessing their proximity to certain criteria. For the MULTITEST CD010, the main calibration characteristics are: ultrasonic thickness gauge linearity and optical thickness gauge linearity. It is performed using the stepped reference block RBC 1 (Fig. 2). Two or more calibration thicknesses (A, B, C, D) are measured on the reference and are then used to set the thickness gauges.

- Calibration procedure. For the MULTITEST MC010, the main calibration actions are as follows:

- Selection of a representative reference sample for laboratory tests using the following information: type of test material (brand, manufacturing technology, hardness, mechanical and elastic properties, etc.). It is used to consecutively build the following correlations (Fig. 3):

- Building correlations of the $E_{NB} = F(I_N, f)$ type;

- Building correlations of the $E_{MAE} = F(I_N, f)$ type;

- Magnetization conditions are selected where $I_{opt} = I_N /f = max.$ and the main calibration characteristics are as follows:

I_N – magnetizing current magnitude, f – magnetizing current frequency; E_{NB} – magnetic noise voltage; E_{MAE} – magnetoacoustic emission voltage.

Reference samples of the material are tested under optimal current I_{opt}. The characteristics of E_{NB} ans E_{MAE} are captured and compared with the representative reference laboratory samples. The values obtained are entered. The applicability of the magnetization conditions to the non-destructive testing of the test material is shown. Calibration and setting are performed once for a series of samples. The calibration is performed according to the following algorithm:

- The $E_{NB}(f)$ correlations for the reference samples and for several groups of standard samples of the test material are obtained through automatic scanning. The resulting correlations are approximated by functions of the type:

$$E_{NB} = (a_k f^2 + b_k f + c_k)^{-1} \quad (1)$$

The correlations (1) are used to determine the optimal frequency $f_{B,opt}$ and, at that frequency, the magnetizing current $I_N = E_{NB}(I_N)$ is used to determine the correlations of the noise voltage E_{NB}. The resulting correlations are approximated by functions of the type:

$$E_{NB} = a_k exp\{ b_k [exp(ckI_N)]\} \quad (2)$$

The sample's technological conditions with respect to the frequency f and the magnetizing current I_N are optimized by analyzing the correlations obtained using the procedure for finding the maximum differences between the values of the approximated data.

(a) The optimal frequency and optimal magnetizing current are determined. The correlations (1) are approximated by square equations of the type:

$$f_B^2 + af + c = 0 , \quad (3)$$

the roots of which represent the optimal frequency $f_{B\ (opt)}$, and then the correlations $E_{NB}(I_N)$ and $E_{MAE}(I_N)$ for the groups of standard samples are obtained at that frequency (Fig.2). These correlations are approximated by non-linear equations of the type:

$$Exp[\varphi_l(I_N^{(1)})] - Aexp[\varphi_l(I_N^{(2)})] = 0, \quad (4)$$

(b) Equations (4) are used to find the maximum differences between the values of the approximated data, which are in turn used to find the optimal value of the magnetizing current I_{Nopt} (Fig. 3). Under this magnetizing current, E_{NB} and E_{MAE} will be measured in real samples with unknown structural and mechanical characteristics.

The main actions taken to calibrate the MULTITEST CD010 are as follows: The operating range is set as described in the device's instructions, according to the minimum and maximum thickness of the test material, so that the range of the material's real thicknesses is within the operating range. For this purpose, two consecutive measurements are made on two sections (with minimum and maximum thickness) of the reference RCB 1 (Fig. 2) and are adjusted so that:

$$d_{ye1} = d_{oe1} = d_{e1} \ \text{и} \ d_{ye2} = d_{oe2} = d_{e2} , \quad (5)$$

where: d_{e1} , d_{e2} – actual thickness measured on the two sections of the reference (Fig. 2); d_{oe1} , $d_{oe\ 2}$ – thickness of the same two sections measured with an optoelectronic sensor; $d_{y\ e1}$, $d_{\ ye2}$ – relative thickness of the same two sections measured by ultrasound. The formula is used to calculate the ultrasound velocity:

$$C = k\left(d_y / d_o\right)C_e \tag{6}$$

The following formula is used to calculate the attenuation coefficient:

$$\delta_t = \frac{(A_1 - A_n) - B}{2d_o(n_1 - n_n)}, \tag{7}$$

where: C_e – speed of ultrasound in the reference (*m/s)*; k - coefficient of proportionality representing external conditions; d_y – relative thickness of the material measured by ultrasound; d_o – actual thickness measured with an optoelectronic sensor; δ – attenuation coefficient (*db/m*); n_1 and n_2 – number of pulses compared; *A* – amplitudes of ultrasound pulses compared.

- Apparatus. For the ultrasound method, the specially designed DK100 testing jaws are used for calibration in order to simultaneously capture the calibration data from the optoelectronic transducer and the ultrasonic piezoelectric transducer.

4.4. Metrological assurance

The metrological assurance of the MULTITEST MC010 is performed using the following types of reference samples:

- Reference sample used to ensure the results are reproducible. It is made of Armco (low carbon) iron with a surface cleared up to $R_a<0.3mm$ and with known magnetic characteristics. Before proceeding, the $E_{NB} = F(I_N)$ correlation is captured for the operating conditions present when the transducer selected for the testing is switched on. The correlations obtained are compared with those obtained from the initial measurements and it is decided whether the results obtained using the device and transducer in question are reproducible. E_{NB} and E_{MAE} are respectively magnetic noise and magneto-acoustic parameters and I_N is the magnetizing current.

- Reference samples of the test material. Their shape and dimensions are determined by the devices and apparatus used to test the samples. The surfaces are polished using a special technique to prevent their finish from having an effect. Depending on the source material, appropriate heat and chemico-thermal treatments are used to release the initial mechanical stresses. The reference samples are prepared – taking into account the magnetic noise anisotropy of the ferromagnetic materials – by cutting them in the direction of and perpendicular to the magnetic anisotropy. The reference samples are intended to obtain the basic correlations of the magnetic noise characteristics E_{NB} and E_{MAE} of the structure and the mechanical characteristics of the ferromagnetic samples after heat treatment, casting or extrusion.

The metrological assurance of the MULTITEST CD010 is performed using the following types of reference samples:

- Reference sample used to ensure the results are reproducible. It is made of low carbon (Armco) iron with a surface cleared up to $R_a<0.3\ mm$, with an attested transverse ultrasonic wave velocity.

- Stepped reference block RCB 1 (Fig. 2). Two or more calibration thicknesses (A, B, C, D) are measured on the reference and are used to set the device's depth gauge.

4.5. General testing methodology

Once the devices are calibrated as described above, the system can be tested:

• Subject of testing/measurement. The subject of testing is the MULTITEST automated system for comprehensive non-destructive testing of the structure and mechanical properties of metal materials. The MULTITEST automated system includes:

- The MULTITEST MC010 modular device used to measure the magnetic noise and magneto-acoustic characteristics of samples and products made of ferromagnetic materials;

- The MULTITEST CD010 modular device used to measure the velocity and attenuation of ultrasonic waves in metal materials;

- Apparatus – DK100 testing jaws, relevant transducers and laptop used to make the settings and process the results;

- Necessary documentation and software for the system (Operating Instructions, reference samples, Database, Calibration and Testing Methodologies, etc.)

• Purpose of testing/measurement. Assess the accuracy of the method and system used to measure reference samples. Determine the correlations between the non-destructive parameters and the technological properties of the groups of reference samples. Establish the testing suitability of the relevant metal material of the samples to the non-destructive measurements defined by the terms of reference.

• General. The tests/measurements are carried out on the basis of the following standards and technical documents:

- Terms of Reference;

- Operating instructions of the testing/measurement equipment;

- E1476 - 92 Standard Guides for Metal Identification, Grade Verification, and Sorting;

- E1316 - 92 Standard Terminologies for Nondestructive Examinations;

- BDS ISO 5725. Accuracy (trueness and precision) of measurement methods and results;

- ISO Guide 35-1989;

- Operating instructions of the MULTITEST CD010 modular device for making measurements by ultrasound methods;

- Operating instructions of the MULTITEST MC010 modular device for making measurements by Barkhausen methods;

- Operating instructions of the MULTITEST automated system;

- Database;

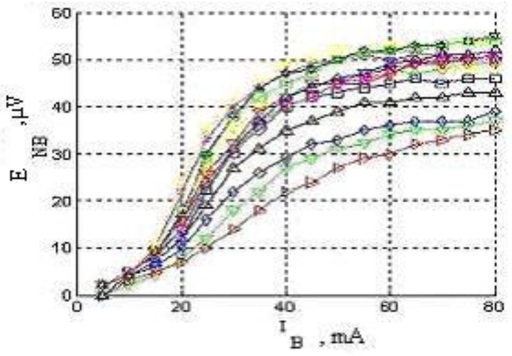
- Automated data processing and assessment software;

- EAL-EA-4/02 Expression of Uncertainty of measurement in Calibration;

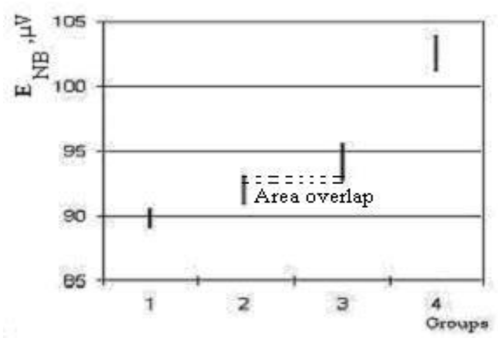
- Test/measurement reports.

5. Experimental testing and discussions

Specific non-destructive testing methods for the hardness (heat treatment) of samples made of alloyed structural steel 43CrMo4 have been developed to test the data processing and assessment system. Standard (reference) samples are prepared, classified into groups with the same mechanical properties according to 3.2. – System of pre-training using references samples. The reference samples have the following dimensions: ⌀30x20mm, and are made of bars of rolled iron which are subjected to different degrees of heat (quenching and tempering). The belonging of the reference samples to the relevant group with the same mechanical properties is confirmed by chemical analysis and mechanical hardness testing.



(a) $E_{NB} = F(I_B)$



(b) Single-parameter interval assessment

Fig.3. Single-parameter confidence intervals of E_{NB}

Fig. 3a and Fig. 3b show graphs of the procedure for determining the testing suitability and the single-parameter interval assessments of the groups of reference samples to the non-destructive parameter E_{NB}.

The single-parameter confidence intervals of the second non-destructive parameter E_{MAE} are obtained in the same manner and then, according to the methodology, the two-parameter interval assessment – characteristic confidence areas of the two parameters E_{NB} and E_{MAE} – are built, as shown in Fig. 4.

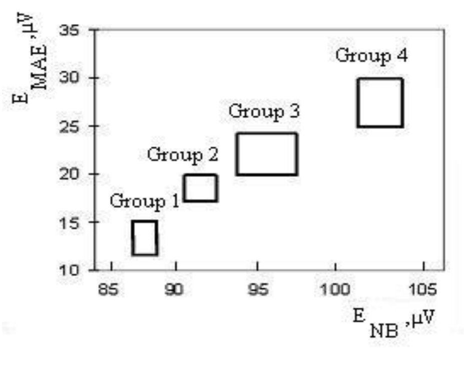


Fig. 4. Characteristic areas for the groups of reference samples.

Figure 3b shows that, when only one E_{NB} parameter is used, the confidence intervals of Groups 3 and 2 will overlap and will therefore be difficult to distinguish. A similar conclusion can be drawn when only the E_{MAE} parameter is used. When the two parameters are used together, the characteristic areas do not overlap (Fig. 4), thereby increasing the probability of correct classification of the test material by structure or mechanical properties. Depending on the characteristic areas formed by the reference samples, for example, if Group 3 is selected as suitable, the tester can proceed to the classification of real parts or materials. Similarly, the system can perform non-destructive testing with other reference samples made of different metal materials (sintered materials, cast iron, battery cathode materials, etc.) using additional non-destructive parameters, such as ultrasound velocity and attenuation or thermoelectric voltage [5,6].

6. Conclusion

The possibility of comprehensive non-destructive testing of the mechanical properties and the structure of samples made of structural steel has been proved.

It is often appropriate to classify samples and products made of structural steel into groups with the same degree of heat treatment (hardness) using two-parameter non-destructive testing.

The testing of the automated system has proven that it can be used in non-destructive testing of the heat treatment and the structure of samples and products made of metal materials.

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