Metrological aspects of an automated method for measuring electrophysical parameters of soft magnetic materials

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Abstract. The structure of an automated system for measuring magnetic-hysteresis loops, normal magnetization curve, magnetic permeability with an error of no more than ± 1% is proposed. The measuring principle is based on the inferential measurements of the magnetic induction and the coercive force by integrating the secondary voltage and the excitation current. As a result of metrological analysis, an increase in the measurements accuracy is achieved both by improving the hardware implementation and calibrating the measuring channels, by introducing a correction for the systematic component of the error.

1. Introduction
The relevance of the study of the electrophysical parameters of magnetic materials is due to their wide application in power electronics devices, in motors, generators [1], as well as in micromechanical systems [2]. Experimental studies of the dependences of the parameters of magnetic materials make it possible to discover new directions for their use. For example, in [3], the results of measurements of hysteresis loops of a high-temperature magnetocaloric alloy are presented, which confirm the appearance of an additional phase transition near a temperature of 315 K. The article [5] proposes a non-destructive microwave method for measuring the electrophysical properties of materials, based on the method of transmission and reflection of a plane monochromatic wave through layered materials with a measurement error of ± 2%. The analysis of the listed and other known instruments for measuring the electrophysical parameters of magnetic materials confirms the relevance of improving the principles and methods of measurements in order to increase their accuracy by performing metrological analysis.

2. Relationships between the parameters of soft magnetic materials
Magnetically soft materials are capable of magnetizing in weak magnetic fields (voltage less than 800 A / m). Soft magnets have low coercive force, low hysteresis loss and high magnetic permeability. A measure that determines the softness of a magnet can be the value of the static relative magnetic permeability μ: its initial values are in the range from 102 to 105; the maximum values belong to the interval from 103 to 106, and the losses due to magnetic hysteresis do not exceed 102 J / m3 per one magnetization reversal cycle.

The behavior of a ferromagnet is described by the dependence of the polarization J (magnetization M) on the magnetic field strength H. The magnetic induction is related by the relationship to the quantities M, J, and H as follows:

\[ B = \mu_0 H + \mu_0 M = \mu_0 H + J \]  

(1)
where \( \mu_0 = 4\pi \times 10^{-7} \text{H} / \text{m}^2 \) - magnetic constant (also called vacuum magnetic permeability).

In fact, expression (1) is a macroscopic result of an extremely complex sequence of microscopic processes in which, by a combination of displacements of domain walls, rearrangement of the domain structure, and rotations of the magnetic moments, the system reacts to a change in the applied field \( H \), making a transition through a sequence of metastable states with minimum energy. These processes are associated with irreversibility and losses, as well as with various behavior of the \( J \) (\( H \)) dependence, for which the phenomenon of hysteresis is inherent. Due to hysteresis, any point on the plane \( (J, H) \) can be crossed by an infinite number of trajectories, depending on the history of the process. For magnetic materials, two basic states are determined: saturation, when all domains are oriented in the direction of the external field, and demagnetized state \( (H = 0, J = 0) \). The latter is achieved either by starting from saturation \( (J = J_s) \) and a smooth decrease in the amplitude of the applied ac field to zero, or by cooling the sample to the Curie temperature in the absence of any field. The curve obtained after thermal demagnetization is called the primary curve. Most often, the demagnetization process is performed using a decreasing alternating field, and then the initial magnetization curve is measured. Figure 1 shows the hysteresis loop of a ferromagnet, measured using a prototype of the automated installation under development for measuring the parameters of magnetic materials.

![Figure 1.](image)

Figure 1. The result of measuring the dependence \( B \) (\( H \)) in the form of a hysteresis loop using a model of an automated setup for measuring magnetic parameters.

The hysteresis loop contains magnetic properties and materials can be classified according to the value of its parameters. Coercive field \( H_c \), residual polarization \( J_r \), maximum permeability \( \mu_p = B_p / H_p \), initial permeability and energy loss \( W \) are the main parameters by which the properties of materials can be estimated. The composition of the material actually determines the values of the so-called internal magnetic parameters, such as the Curie temperature, saturation magnetization, magnetic anisotropy constants and magnetostriction constants, which, in turn, affect the magnetization process depending on the structure of the material (for example, crystallographic texture, grain size, foreign phases and lattice defects). Through the correct choice of composition and suitable metallurgical and heat treatment, super soft magnets can be obtained, in which the coercive field can reach values below 1 A / m with a relative permeability of the order of 105. But it should be emphasized that it is necessary to take into account a number of additional properties, such as thermal and structural...
stability, sensitivity of magnetic parameters to stress, mechanical properties and workability, thermal conductivity and flexibility of reaction to thermomagnetic treatment.

The final conclusion about the applicability of a magnetic material in solving a specific problem will be the assessment of all these properties.

The most common structural material, iron, exhibits soft magnetic properties. The addition of a few percent of Si impurity causes noticeable changes in the physical, mechanical and magnetic properties of iron. Such an alloy is called silicon electric steel, in which iron is the base base. The silicon content in electrical steel provides high electrical resistance and increases the stability of the alloy, helps to increase the magnetic permeability, due to the prevention of the formation of an undesirable phase of cementite Fe₃C. In addition to improving the characteristics, the silicon impurity also has a negative effect on the alloy. Among the negative effects are an increase in the brittleness of the alloy and a decrease in the saturation magnetization. Despite this, electric steel is the main soft magnetic material for mass consumption due to its low cost.

Ni + Fe alloys with a predominant concentration of Ni are called permalloy. The presence in the composition of nickel provides this alloy of a magnetic material with resistance to corrosion and good ductility, which makes it possible to produce thin sheets of this metal that are easy to machine. The magnetic properties of permalloy are largely determined by the chemical composition; therefore, two main types of alloy can be distinguished: high-nickel, containing up to 80% nickel, and low-nickel.

The main qualities of this alloy are high values of resistivity and magnetic permeability. Permalloy alloy is quite difficult to manufacture, which is reflected in its high cost.

3. Method for determining static magnetic characteristics

The standard described in GOST 8.377-80 applies to precision soft magnetic materials with a coercive force up to 4 kA/m and establishes a measurement procedure for determining the main magnetization curve and magnetic hysteresis loop for samples of these materials and their parameters; maximum magnetic permeability; the squareness coefficient of the magnetic hysteresis loop; coercive force on magnetization; temperature coefficients of the above parameters, as well as the requirements for these samples and measuring equipment.

The statistical magnetic characteristics and parameters of the samples are determined using an installation (Figure 2), consisting of measuring instruments and devices, the requirements for which are set out below.

The main magnetization curve is determined starting from the lowest required field strength, gradually moving to higher values. Returning from larger values to smaller values is not allowed. The coordinates of each point of the main magnetization curve (magnetic field strength and magnetic induction) are measured according to the following sequence:

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- Calculate the values of the magnetizing current I in amperes, corresponding to the values of H in amperes per meter, at which the magnetic induction will be determined, according to the formula

\[ I = \frac{\pi H(D_H + D_B)}{2\omega_1} \]  \hspace{1cm} (2)

instead of \( \omega_1 \), the number of turns of the magnetizing device (if used) is substituted.

- Connect the magnetizing winding to the power source using the \( S_2 \) switch; the measuring winding is disconnected from the galvanometer (webmeter).

- Switch \( S_1 \) switch on the current and with the help of adjusting devices \( R_1 \) and \( R_2 \) (switch \( K \) open) set the lowest current value obtained by the formula (4) according to any of the ammeters.

- Change the direction of the current at least 10 times with the \( S_1 \) switch. The switching frequency should be no more than two operations per second.
Switch $S_3$ turn on the measuring winding and, by changing the direction of the current, determine at this moment the deflection of the galvanometer pointer or the weemeter reading. The measurements are repeated many times and the results are averaged to reduce the random component of the measurement result.

**Figure 2.** Connection diagram of the installation elements for determining the static magnetic characteristics and parameters of the samples: $R_1, R_2$ - adjusting devices; $A_1, A_2$ - ammeters; $S_1, S_2, S_3$ - double-pole switches; $K$ - key; $W_1$ - magnetizing winding of the sample or magnetizing device; $M$ - exemplary coil of mutual inductance; $R_3$ - resistance box; $G$ - ballistic galvanometer or webmeter; $W_2$ - measuring winding of the sample or measuring coil.

4. **The structure of the system for the magnetic materials parameters measuring**

The authors have developed an automated information and measurement system (IMS) for studying the parameters of magnetic materials (Figure 3), based on inferential measurements of the magnetic induction and the coercive force by integrating the secondary voltage and the excitation current, respectively.

**Figure 3.** Block diagram of IMS for studying the soft-magnetic materials parameters.

A toroid core is made of the investigated soft-magnetic material. The measuring unit generates the excitation current in the winding I and converts the EMF of the winding II into a code proportional to the magnetic induction in the investigated soft-magnetic material.

5. **Magnetic induction transfer function**

Installation control and processing of measurement results is carried out according to unique methods, which are implemented in software using a computer (PC). In particular, both the Preisach model and the modeling methods previously tested by the authors on the hysteresis loops of ferroelectric
materials were used to simulate magnetic-hysteresis loops [6, 7]. The value of the desired magnetic induction $B$ is determined according to the following expression:

$$B = \frac{\int \varepsilon(t) dt}{S \cdot n_H}$$  \hspace{1cm} (3)

where $B$ – magnetic flux; $S$ – the core cross-sectional area; $n_H$ – number of magnetizing coil rings; $\varepsilon$ - EMF of the measuring winding, which is converted into a digital code by means of an analog-to-digital converter (ADC) $N_B$:

$$N_B = \text{Ent} \left[ \frac{\varepsilon t_p + 0.5q}{\tau} \right]$$ \hspace{1cm} (4)

where Ent[] - integer symbol; $\tau$- integrating time constant; $t_p$- pulse duration at the input of the integrator as part of the measuring unit; $q$ – ADC quantization step.

As a result of the metrological analysis of the developed IMS, it was found that the main instrumental error in the magnetic induction measuring is due to the errors of the integrator based on the operational amplifier, the error in measuring the cross-sectional area $S$, and the metrological characteristics of the ADC. In order to minimize the integration error, it is proposed to use an integrator, in which the capacitor discharge is realized with a voltage that is formed by a discharge stage on an operational amplifier at the integrator output.

6. Conclusion

The proposed automated IMS performs automated measurements of magnetic-hysteresis loops, normal magnetization curve, magnetic permeability with an error of no more than ±1%, as well as processing and displaying the results obtained on the monitor screen in graphical and tabular form, saving them in a database for further research. An increase in the measurement accuracy is achieved both by improving the hardware implementation and by calibrating the measuring channels by introducing a correction for the error systematic component.

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