

ELECTROMAGNETIC TRANSDUCER FOR MEASURING
THE THICKNESS OF THE HEAT-RESISTANT
FERROMAGNETIC FILM OF TURBINE BLADES

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Abstract

This article presents the design features and general modelling of a Hall-effect-based transducer for measuring the thickness of the ferromagnetic coating, capable of operating in a vacuum chamber at a temperature of 300 °C. The calculation of the Hall constant and the potential difference across the sensing element due to the influence of a static magnetic field, with the corresponding distribution of magnetic field strength, magnetic flux density, and voltage, has been performed. The simulation model was built in the Maxwell software based on the finite element method, which confirms the analytically obtained functional dependencies. The significance of the obtained results lies in the possibility of ensuring the specified accuracy and, accordingly, the efficiency of measuring the thickness of the heat-resistant metal film on turbine blades.

Key words: modelling, sensor, turbine blade, heat-resistant coating, Hall effect, thickness measurement, magnetic field

Introduction. Turbine construction is an integral branch in developed countries, where product quality control is subject to careful analysis. Constant monitoring of the heat-resistant film plays a crucial role during the vacuum plasma

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spraying process of the protective material onto the blades [1, 2]. The quality of the blade significantly depends on the thickness of the deposited coating, as well as on the deviation of this thickness from the specified value. Many research groups have studied the challenges of coating thickness measurement and have established requirements for measuring instruments [3–5], in particular: sensors must be high-performance, provide sufficient measurement accuracy, and interface with computing devices during automated measurement.

To date, various research institutions have developed numerous inductive sensors that can be used to measure coating thicknesses in laboratories and in production environments. The classification of sensors is based on their operating methods and principles. One of the methods in this field is eddy current testing [6, 7], which relies on the generation of eddy currents by a coil in a conductive plate. The coil itself acts as a sensing element with a variable magnetic field, the electromagnetic parameters of which depend on the thickness of the plate [8, 9]. The main advantages of eddy current methods are their low cost and reliability [10–13]. The disadvantage is the significant influence of the working gap between the sensor and the plate on the measurement results. Another type of sensor is based on the Hall effect, where, unlike the previous method, a constant magnetic field is used in the coil, and a Hall sensor that measures the magnetic field induction acts as the sensing element [14, 15]. This approach makes it possible to significantly improve the accuracy of measuring the thickness of the heat-resistant film on ferromagnetic substrates. For example, EJSING et al. [16] presented a planar Hall effect sensor for detecting magnetic micro- and nanoparticles. The sensor's response to an applied magnetic field was measured with and without 2 μm and 250 nm magnetic bead coatings.

The literature review shows ongoing intensive improvement of heat-resistant film thickness measurement tools, aimed at enhancing their metrological characteristics. This work focuses on studying an electromagnetic transducer for measuring the thickness of ferromagnetic thermal barrier coatings on turbine blades using computer modelling.

Scheme and method of measuring thermal resistant coating in a vacuum spraying chamber. The measuring system consists of an inductance coil with a high Q-factor and a sensing element (measuring plate) based on a Hall sensor. This sensor measures the thickness of the heat-resistant film using the witness sample method and is connected to the measuring unit. Its scale is calibrated in units of the deposited film's thickness (microns) and may be influenced by the relative position of the substrate onto which the material is deposited and the sensor (for certain sputtering methods and types of vacuum chambers). The design of the measuring transducer is illustrated in Fig. 1. The sensor is situated within a vacuum chamber where a ferromagnetic material is deposited onto it and operates in a broad temperature range up to 300 °C. Furthermore, the measuring unit of the sensor is located outside the vacuum chamber.

When a current flows in the direction indicated by the arrow in Fig. 1, electrons drift with speed ν in the opposite direction. Each such electron e is acted upon by the Lorentz force F_L from the side of the magnetic induction B .

$$(1) \quad \bar{F}_L = e [\bar{\nu} \times \bar{B}] .$$

The direction of this force is determined by the drill rule. Since the angle between ν and B is 90° , the numerical value of the Lorentz force (which is equal to the product of the particle charge q by the vector product of its velocity ν and the magnetic induction B) is:

$$(2) \quad F_L = q\nu B.$$

Under the action of the Lorentz force, electrons are deflected to the outer boundary of the plate (Fig. 1), charging it negatively. On the opposite face, positive charges accumulate that are not compensated. As a result, a transverse electric field arises, the intensity of which is $\bar{E}_H$. This field acts on each free electron with the force F_H :

$$(3) \quad \bar{F}_H = -e\bar{E}_H.$$

Field $\bar{E}_H$ acts on electrons with a force $F_H = -qE_H$ directed against the Lorentz force.

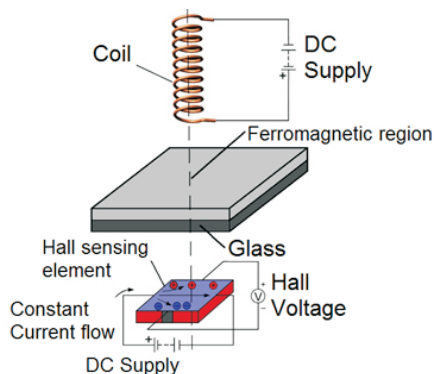


Fig. 1. Scheme of the transducer for measuring the thickness of thin metal films

$$(4) \quad E_H = \frac{1}{ne} B j = R_H B j,$$

where $R_H = 1/ne$ is the the Hall constant obtained without taking into account the distribution of electrons by velocities when using Fermi–Dirac statistics. The Hall constant is inversely proportional to the concentration of electric charge carriers.

Based on the determined value of the Hall constant, it is possible to find: 1) the concentration of current carriers in conductors and semiconductors; 2) conductivity type, that is, the sign of the current carriers in the semiconductor, since the sign of the Hall constant coincides with the sign of the charge of the current carriers. To find the Hall potential difference, it is necessary to take into account the current through the plate and the cross-sectional area of the plate

$$(5) \quad U_H = R_H \frac{BI}{a}.$$

In the general case, the electrical resistance R of a metallic Hall measuring plate is directly proportional to its length L and inversely proportional to the cross-sectional area S :

$$(6) \quad R = \rho \frac{L}{S},$$

where the coefficient ρ is called specific resistance and is a characteristic of the material from which the conductor is made.

The material used at a temperature of 300 °C for the Hall measuring plate has certain properties of electrical conductivity and thermal conductivity. Electrical conductivity is inversely proportional to electrical resistance. Since atoms create an obstacle to the passage of current, the resistance index of substances varies. Another important property is thermal conductivity, which is characterized by the process of energy transfer between atoms and molecules from hotter objects to colder ones, carried out through the chaotic movement of particles. The coefficient of linear thermal expansion is defined as the ratio of the change in the linear dimensions of the material to the change in temperature. So, this is the relative change in length per degree of temperature change:

$$(7) \quad l = l_0(1 + k[t_2 - t_1]),$$

where l_0 is the initial length of the body at temperature t_1 , l is the final length of the body at temperature t_2 , k is the coefficient of linear thermal expansion. In calculations, the volume expansion of the measuring plate can be considered a linear expansion in three directions.

Results of computer simulation of the interaction of a three-dimensional magnetic field with a Hall sensing element. A simulation model of the measuring transducer. The authors developed a simulation model (Fig. 2), which consists of an inductance coil $L = 21$ mH in the form of a solenoid with a cross section of 150×150 mm, a glass substrate of $300 \times 300 \times 5$ mm, onto which a heat-resistant material with a thickness of 1 to 500 μm is sprayed, and a gold foil is used as a Hall sensing element with dimensions $l = 50$ mm, $b = 50$ mm, $a = 1.5$ mm (l – length, b – width, and a – thickness – all dimensions taking into account thermal expansion at a temperature of 300 °C). For computer modelling,

the constant current in the coil is set to 500 A·turns (Current 1), and in the sensing element – 30 mA (Current 2). Moreover, Current 2 is supplied to the Hall sensing element through a source of stabilized current, which makes it impossible for the electrical parameters of the sensing element to change due to thermal expansion.

The setup used in Maxwell simulations possesses the following parameters: the modelling was carried out for magnetostatics; its maximum number of passes is 10 with a percent error of 1%; refinement per pass is 30; the minimum number of passes is 2; the minimum number of converged passes is 1; and the nonlinear residual was set to 0.001.

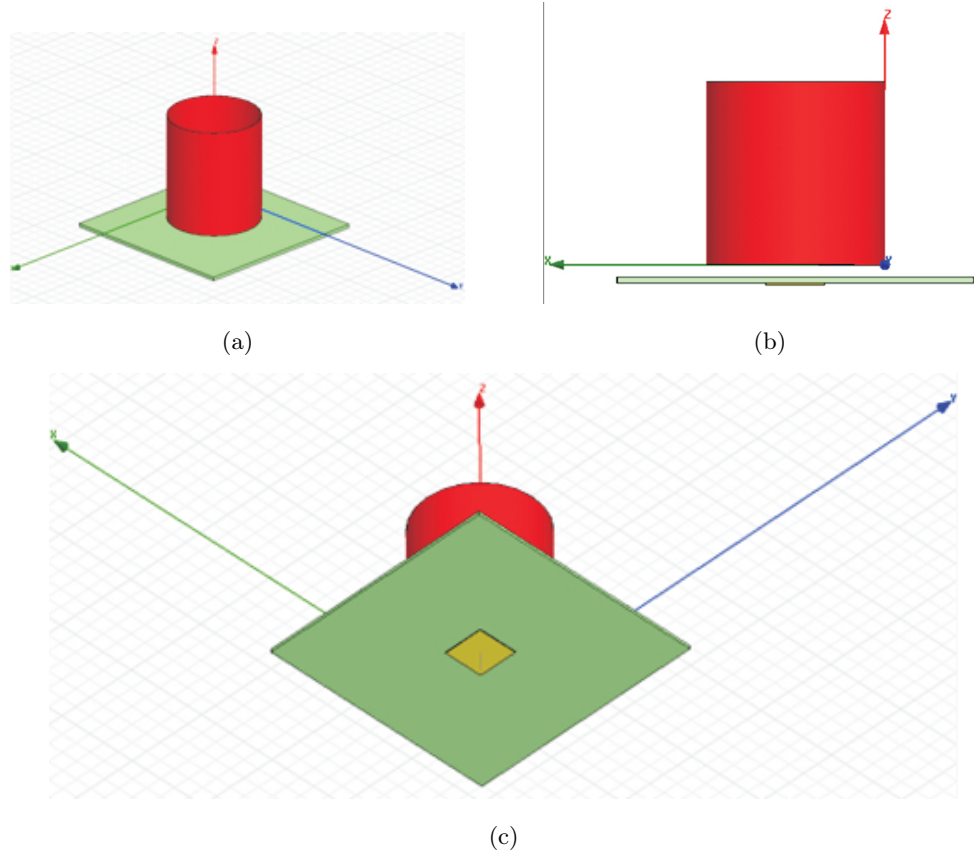


Fig. 2. General view of the computer model of the stand for measuring the thickness of spraying heat-protective material: (a) View from the mountain at an angle; (b) View from the side; (c) View from below at an angle

With the help of the developed computer model, the main electromagnetic parameters were analyzed, namely: magnetic flux density (induction) and magnetic field strength depending on the gap between the coil and the Hall sensing element. The simulation results are summarized in Table 1, where the following notations are used: δ – distance between coil and glass plate, B_A – average value

T a b l e 1

Characteristics of the magnetic field
in the proposed measuring system

δ , mm	B_A , mTl	H_A , A/m
3	1.85	1480
5	1.72	1400
7	1.65	1290
9	1.55	1190
11	1.54	1250
13	1.53	1210
15	1.49	1190
17	1.41	1100
19	1.35	1070
21	1.32	1050
23	1.27	970

of the induction at the midpoints (parallel to the xOy plane in the centre of Hall sensing element), H_A – average value of magnetic field strength at the midpoints. For further research, an air gap of 10 mm was chosen between the coil and the Hall sensing element. The distribution of magnetic flux density and magnetic field strength in the middle section (parallel to the xOy plane) of the Hall sensing element was obtained for this configuration of the measuring system components with a distance of 10 mm between the coil and the glass substrate.

Study of the measuring sensor for different metals. The process of forming a protective coating on turbine blades involves applying different layers of metals. Depending on the type of metal and operating conditions, nickel, cobalt, or their combination can be used (iron can also be used in steel blades).

The authors conducted a series of experimental measurements of the thickness of ferromagnetic metals in the thermal barrier coating: iron, nickel, and cobalt. The comparative characteristics of the change in magnetic field strength depending on the distance between the coil and the glass substrate when measuring samples of the same thickness for different sprayed metals are presented in Fig. 3. Initial data for numerical analysis and modelling include all the necessary information about the properties of materials, namely: relative magnetic permeability (nickel – 600, cobalt – 250, iron – 4000), specific electrical conductivity (iron – 10 300 000 Siemens/m, nickel – 14 500 000 Siemens/m, cobalt – 10 000 000 Siemens/m according to the Maxwell library).

The obtained results of the equivalent ratios of the thickness of metal deposition to the operating parameters of the electromagnetic transducer show the influence of the deposition thickness on the magnetic flux density and magnetic field strength in the middle section of the Hall sensing element parallel to the xOy plane in the range of ferromagnetic metal deposition from 0 to 500 μm .

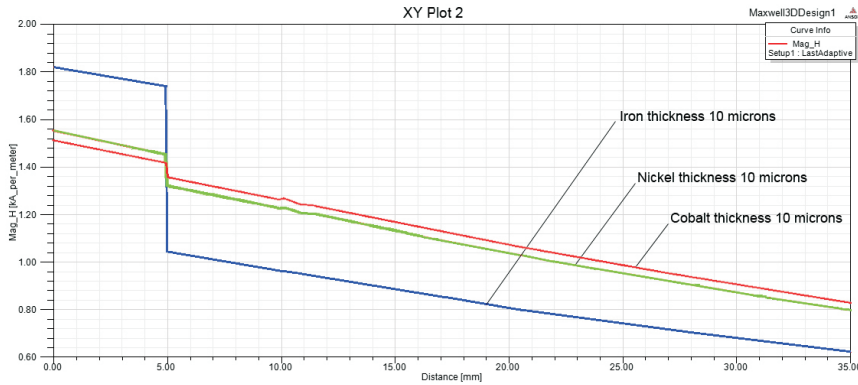


Fig. 3. Characteristics of changes in the magnetic field strength in the gap for heterogeneous coatings of the same thickness

Based on the obtained data, the Hall constant and the voltage on the sensitive element were calculated, which decreases with decreasing magnetic field strength. The results shown in Fig. 3 demonstrate three characteristic areas of the magnetic field change along the z axis between the coil and the gold foil. The first area corresponds to a linear change in the field in the air gap, the second to the thickness of the ferromagnetic coating on the glass substrate and is characterized by a sharp decrease in the field strength, and the third is again a linear dependence with a slight nonlinearity due to the passage of the field through the sensitive Hall element. The largest changes in the magnetic field strength are observed when modelling a converter with an iron coating.

The influence of structural and thermomechanical factors is discussed in [17] and may be useful for this study. In [18,19] algorithmic approaches are used to describe transport phenomena in multiphase media, demonstrating the effectiveness of combining physical models with computational methods. These approaches can also be consistent with this study, which uses finite element modelling.

Conclusions. In this work, the issue of determining the thickness of a protective ferromagnetic metal coating on a turbine blade with the specified accuracy is considered. This issue is addressed through the proposed design of a Hall-effect-based sensor and a computer study of determining the thickness of a ferromagnetic metal film deposited in a vacuum during the deposition process. The considered sensor design is capable of functioning in a vacuum chamber at operating temperatures ranging from 25 to 300 °C.

Computer modelling of simulation models of the electromagnetic transducer was carried out to determine the thickness of ferromagnetic coatings: iron, nickel, and cobalt, which are actively used in protective coatings of turbine blades. The obtained results demonstrate the feasibility of choosing the material for the Hall sensing element and the high accuracy of analytical calculations of its parameters for different coating thicknesses.

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