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DEMAGNETIZING FIELD IN A LENGTH OF THE ELECTRICAL STEEL SAMPLE CLOSED YOKE AND MAGNETIZED IN A COIL

ABSTRACT *In this paper distribution of demagnetizing field of a rectangular sample made of an anisotropic silicon electrical steel was determined analytically. The measuring windings were wound on the sample, which was placed in an homogenous external magnetic field in a coil. The distribution of the magnetic induction was measured and based on it demagnetizing field distribution was calculated.*

Keywords: *electrical steel, magnetic induction, tangential component of magnetic field intensity, demagnetizing field*

1. INTRODUCTION

Determination of magnetic properties of ferromagnetic materials requires the measurement of basic magnetic quantities such as magnetic induction B and magnetic field intensity H and their mutual assignment what means the function $B = f(H)$. Homogeneous distribution of tangential component of magnetic

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field intensity on the surface of the sample should be ensured to properly measurement magnetic induction and magnetic field intensity [1]. This condition is almost unreachable due to the fact that sources of demagnetizing field are generated by the normal component of magnetic induction to the surface of magnetizing sample of electrical steel.

2. MEASUREMENT OF MAGNETIC INDUCTION B AND MAGNETIC FIELD INTENSITY H:

The accuracy and the ability to measure magnetic induction and magnetic field intensity result from the elementary laws of electrodynamics, which are determined by Maxwell's equations [2]. The basic ways of measuring the magnetic induction B and magnetic field intensity H were obtained from these equations, which show clearly the relationship between magnetic and electrical magnitudes.

Time-varying magnetic field generates a rotational electric field. It is known as Faraday’s law of induction:

$$rotE = -\frac{dB}{dt} \tag{1}$$

where μ is magnetic permeability. The above equation shows the dependence of magnetic induction B from the tangential component of electric field intensity E to the cross-sectional surface of the sample, as defined by the equation:

$$\int_{l(S)} E \cdot dl = -\frac{d}{dt}\int_{S} B \cdot dS \tag{2}$$

Curvilinear integral along a closed path of integration of the electric field intensity E along the curve of integration l is equal to the voltage:

$$\int_{l(S)} E \cdot dl = -e \tag{3}$$

The integral over the surface S limited by a curve l of the magnetic induction B is equal to the magnetic flux φ flowing through this surface:

$$\int_{S} B \cdot dS = \varphi \tag{4}$$

Taking equations (3) and (4) into account, the law of electromagnetic induction was obtained: time-varying magnetic flux φ causes induction of a voltage e in a closed circuit comprising this magnetic flux:

$$e = -\frac{d\varphi}{dt} = -S\frac{dB}{dt} \tag{5}$$

From the above equations derive the existence of two ways of measuring the magnetic induction B: measurement of voltage caused by the vorticity of vector of electric field intensity E or measurement of the electromotive force e induced by time-varying magnetic flux using inductive sensor comprising the sample. It should be noted that value of magnetic induction B determined from above equations is the average value over the cross section of the sample:

$$B_{av} = \frac{1}{S}\int_S B \cdot dS \tag{6}$$

Therefore, a homogeneous distribution of the cross-sectional sample in the measuring area must be ensured to correct measurement of magnetic induction B.

Time-varying electric field generates a rotational magnetic field. It is known as Ampere's law:

$$rotH = \sigma E + \frac{dD}{dt} \tag{7}$$

where σ is conductance and ε is permittivity. In conductive environments at low frequencies dielectric displacement current is negligible compared to the conduction current. Therefore, the formula (7) simplifies to the form:

$$rotH = \gamma E \tag{8}$$

Thus the basic dependence of the magnetic field intensity of the magnetizing current flowing through the test cross-sectional surface of sample is:

$$\int_{l(S)} H \cdot dl = \int_S j \cdot dS = \theta \tag{9}$$

where j is surface current density and θ is magnetomotive force. Depending on whether the chosen path of integration includes the current flow or not, two different solutions are obtained.

If the path of integration does not include the current flow and taking the Stokes law into account, the equation (8) simplifies to the form:

$$\int_S rotH \cdot dS = 0 \tag{10}$$

and it means:

$$rotH = 0 \tag{11}$$

This equation shows that magnetic field intensity H is the irrotational field. Therefore, if any currents do not flow on the surface of the sample, tangential component of magnetic field intensity H is continuous on the border of two environments: ferromagnetic sample and air.

If the path of integration includes the current flow, the flow is proportional to the number of turns N passing through the surface S, through which current i flows:

$$\theta = N \cdot i \tag{12}$$

If the magnetic field intensity H is constant along the path of integration, the equation (12) is simplified for the average length of path of magnetic flux in the sample:

$$H_l = \frac{N}{l_{av}} i \tag{13}$$

where l_{av} is the average length of path of magnetic flux in the sample. It follows that determined value of magnetic field intensity H_l is averaged value at the length of the sample. Demagnetizing field H_d is generated by normal component to surface of sample of magnetic induction. Therefore, determined value of magnetic field intensity H_l is a superposition of an external magnetizing field H_z and demagnetizing field H_d which comes from sources of magnetizing sample [3]:

$$H_l = H_z - H_d \tag{14}$$

From the above equations derive the existence two ways of measuring magnetic field intensity H: the method based on the measurement of current magnetizing the sample and the direct method based on the continuity of the tangential component of magnetic field on the border of two environments with different magnetic permeability. It is very important that the current, flowing on the border of two environments with different magnetic permeability, is equal to zero when the magnetic field intensity is measured by the direct method.

3. MEASURING SYSTEM

A system consisting of a magnetizing coil and the yoke closing the test sample was used to measure. This type of system is often used for measurement of magnetic properties of electrical sheet samples. A rectangular anisotropic silicon electrical steel sample with dimensions of (220x30x0,35) mm was used to determine the magnetic induction distribution. The measuring coils were wounded at half of the length of the sample and they consisted of 21 coils, 9 turns each, as it is shown in Figure 1. Each of the winding included cross-sectional sample over a length of 5 mm.

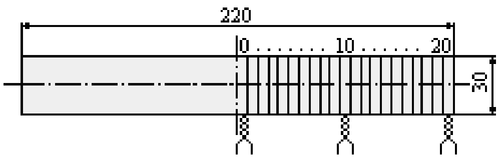

Fig. 1. The electric steel sample with measuring windings used for measurements

The sample was closed by yoke made of five strips of the same electrical steel of the same width and thickness as sample. Omission of decreasing magnetic voltage in the yoke was carried out by increasing cross-section of the yoke. Therefore, the practically the entire magnetomotive force deposited on the length of the sample. The sample was placed in the magnetizing coil. Measurements were performed for sinusoidal magnetic field with frequency 50 Hz. Induced electromotive force was measured with a voltmeter calibrated transmitter average value for the root mean square value for sinusoidal signal.

4. CALCULATION OF DISTRIBUTION OF MAGNETIC INDUCTION

Based on the measured voltage, induced in the measuring coils, the distribution of the electromotive force on the length of the sample was determined. Using the Faraday's law of induction (5), the distribution of magnetic induction on the length of the sample was obtained. The average value of induced voltage measured above-mentioned voltmeter is equal to:

$$U_{av} = \frac{2}{T}\frac{d}{dt}(|\,\phi_m \sin \omega t\,|)\Big|_0^{T/2} \tag{15}$$

where T is a period of sinusoidal signal.

After the operation of differentiation above formula takes the form:

$$U_{av} = \frac{4}{T}\phi_m \tag{16}$$

Taking the form factor FF for sinusoidal signal into account, the root mean square value of induced voltage is:

$$U_{rms} = 4{,}44\, f\phi N \tag{17}$$

where f is frequency of the induced voltage. The magnetic flux ϕ passing through a given surface S is equal to the magnetic induction B and the equation (17) is converted into a formula:

$$B = \frac{U_{rms}}{4{,}44\, fabN} \tag{18}$$

where a is width and b is thickness of the sample.

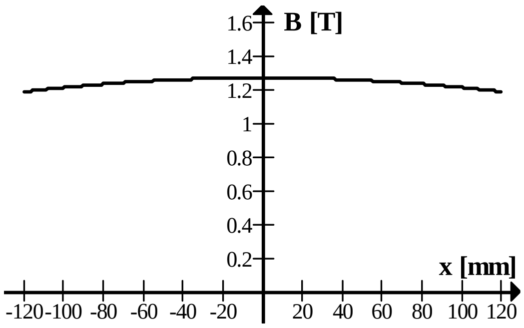

Fig. 2. Measurement results of distribution of magnetic induction on the length of the electrical steel sample

The resulting characteristics of the distribution of magnetic induction on the length of the electrical steel sample, as shown in Figure 2, is determined for a particular state of saturation of the sample, namely for the magnetic induction equal to 1,27 T.

5. CALCULATION OF DISTRIBUTION OF DEMAGNETIZING FIELD

Normal component of magnetization to the surface of the sample of electrical steel M_n is given by the formula [4]:

$$M_n = \frac{B_n}{\mu_0} \tag{19}$$

where μ_0 is a permeability of vacuum. Calculations were performed in the coordinate system (ξ, η, ζ). Two points m and $-m$, lying on the surface of the sample, were chosen. Their coordinates are respectively (ξ_1, η_1, 0) and ($-\xi_1$, η_1, 0), as shown in Figure 3.

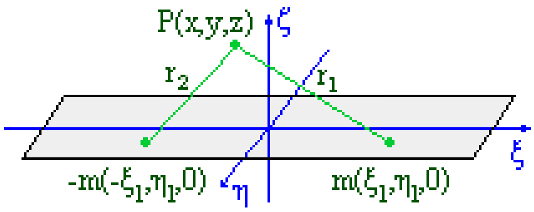

Fig. 3. Illustration of determining the sources of the demagnetizing field

These points represent the sources of demagnetizing field and because of their opposite signs can be treated as a pole of the magnetic dipoles. Then the equation is satisfied:

$$m = M_n dS \tag{20}$$

where dS is the elemental surface. The normal component of magnetization ends up on the surface of the sample sheet, therefore the sources of the demagnetizing field are appeared on this surface. The point P with coordinates (x,y,z) was selected above the surface of the sample. The distance of P from the surface of the sample was assumed equal to 0,2 mm because of the technical possibilities of measuring [5]. The distances r_1 and r_2 of P from the two sources of demagnetization field are equal to:

$$r_1 = \sqrt{(\xi_1 - x)^2 + (\eta_1 - y)^2 + z^2} \tag{21}$$

$$r_2 = \sqrt{(\xi_1 + x)^2 + (\eta_1 - y)^2 + z^2} \tag{22}$$

The potential at the point $P(x,y,z)$ from this dipole was calculated according to the formula:

$$dV(x,y,z) = \frac{M_n d\xi \cdot d\eta}{r_1} - \frac{M_n d\xi \cdot d\eta}{r_2} \tag{23}$$

Therefore, the potential V over the entire surface of the sample sheet can be obtained by the formula:

$$V(x,y,z) = \frac{1}{4\pi} \int_{-110}^{110} \int_{-15}^{15} \left(\frac{M_n(\xi)}{r_1} - \frac{M_n(\xi)}{r_2} \right) d\xi \cdot d\eta \tag{24}$$

The limits of integration are related to the size of the magnetized sample of electrical steel. Based on the equation (24) the distribution of demagnetizing field H_d was determined as a derivative of the potential V with respect to length ξ of test sample of electrical steel:

$$H_d = \frac{dV(x,y,z)}{d\xi} \tag{25}$$

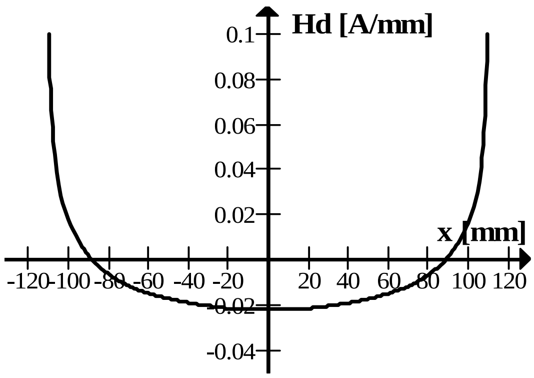

Fig. 4. Distribution of demagnetizing field on the length of the electrical steel sample

Values of demagnetizing field are negative on the central area of test sample, as shown in Figure 4. According to the formula (14), determined value of magnetic field intensity H_l is greater than value of external magnetizing field H_z on this area. Values of demagnetizing field are positive at both ends of the sample, which means the demagnetizing effect occurred, so determined value of magnetic field intensity H_l is less than value of external magnetizing field H_z.

6. CONCLUSIONS

The correct measurement of magnetic properties of sheets or tapes of electrical steel and determine their state of magnetization required to ensure homogeneous distribution of tangential component of magnetic field intensity on the surface of the sample. Occurrence demagnetizing field, generated by the component normal to the sample surface magnetic induction, makes this condition impossible to fulfill. The method allowing for the designation of demagnetizing field distribution based on the laws and equations of electrodynamics is presented in this paper. Taking into account the measurements and calculations, it was found that measured value of magnetic field intensity is higher in the central area of the sample, while at the ends is less than the value of the external magnetizing field.

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POLE ODMAGNESOWUJĄCE NA DŁUGOŚCI PRÓBKI BLACHY ELEKTROTECHNICZNEJ ZWARTEJ JARZMEM I MAGNESOWANEJ W CEWCE

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STRESZCZENIE *W artykule wyznaczono analitycznie rozkład pola odmagnesowującego prostokątnej anizotropowej krzemowej próbki blachy elektrotechnicznej. Uzwojenia pomiarowe nawinięto na próbkę, która została umieszczona w jednorodnym zewnętrznym polu magnetycznym w cewce. Zmierzono rozkład indukcji magnetycznej i na jego podstawie obliczono rozkład pola odmagnesowującego.*

***Słowa kluczowe**: blacha elektrotechniczna, indukcja magnetyczna, składowa styczna natężenia pola magnetycznego, pole odmagnesowujące*