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Magnetoelastic effect in axial stressed Ni-Zn ferrite material in Rayleigh region

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The paper presents new and original results of investigation on magnetoelastic effect in Ni-Zn ferrite formed into ring core and subjected to the axial stress up to 20 MPa. The core was magnetized with relatively low magnetizing field, corresponding to the so-called Rayleigh region. The obtained results indicate, that there is a significant correlation between applied stress and magnetic properties of the material and the Ni-Zn ferrite can be utilized in development of magnetoelastic sensor of force and stress.

K e y w o r d s: ferrite, magnetoelastic effect, axial stress, Rayleigh region

1 Introduction

Ferrites are one of the most important and commonly utilized group of the ferromagnetic materials. They are chemically composed of iron oxide Fe_2O_3 and one or more metallic components [1]. They are mostly utilized in electronic industry as magnetic cores of inductive components. However, there is also a possibility to utilize ferrite materials in sensor application. Magnetoelastic effect is a physical phenomenon involving change of magnetic characteristics and properties of ferromagnetic material under the influence of mechanical stress [2]. Ferrites exhibit high susceptibility to the influence of applied mechanical stress. Thus, they can be utilized as the cores of magnetoelastic sensors of force and stress [3, 4]. Most studies on the magnetoelastic effect in ferrites were performed in the high magnetizing fields, in the near saturation region [5, 6]. However, there is also possible to observe magnetoelastic effect in ferrite magnetized with low magnetizing filed, in the so-called Rayleigh region [7]. From the point of view of application in force and stress measurements, magnetization of the core with low magnetic field decreases the energy consumption of the sensor, reducing the cost of its operation. In the paper new and original results of investigation on magnetoelastic effect in Ni-Zn ferrite magnetized in Rayleigh region are presented. The material was formed into ring core and subjected to the axial stress up to 20 MPa. On the basis of obtained results it could be stated that there is a significant correlation between applied mechanical stress and magnetic properties of the material.

2 Rayleigh region

Rayleigh region refers to the first part of the initial magnetization curve of ferromagnetic materials, where the dependence between magnetic flux density (or magnetization) and magnetizing field can be approximated with the second degree polynomial equation, known as the Rayleigh law of magnetization [8]

$$B(H) = \mu_0 \alpha_R H^2 + \mu_0 \mu_i H \tag{1}$$

where, B is magnetic flux density, H is magnetizing field and μ_0 is magnetic permeability of free space. There are also two coefficients describing magnetic properties of the material in Rayleigh region: initial relative magnetic permeability μ_i and so-called Rayleigh coefficient α_R. This dependence was discovered by Lord John Rayleigh in 1887 during observation of behavior of iron and steel subjected to the relatively low magnetizing fields [9]. Rayleigh also discovered, that hysteresis loop in low magnetizing fields exhibits characteristic lenticular shape, which is in fact the result of branches of the hysteresis loop being two symmetrical, intersecting parabolic curves described by the system of equations [8]

$$B(H) = \mu_0[(\mu_i + \alpha_R H_m)H \pm \frac{\alpha_R}{2}(H_m^2 - H^2)] \tag{2}$$

where H_m is amplitude of the magnetizing field. The lenticular loop is also known as Rayleigh hysteresis loop. The dominant mechanism of magnetization in Rayleigh region is movement of the magnetic domain walls. The linear part of the equation 1 is connected with the reversible elastic deflections of the domain walls while second degree part refers to the irreversible domain walls translations, which are the source of magnetic hysteresis phenomenon in Rayleigh region.

3 Investigated material

The investigated material was nickel-zinc (Ni-Zn) ferrite utilized mostly as material for magnetic cores of inductive components in electronic devices. The material is

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often used in coils with medium Q factor for resonant circuits and filters as well as in wideband transformers. The material is characterized by the positive value of saturation magnetostriction coefficient λ_s, which is important from the point of view of magnetoelastic properties of the material. The investigated ferrite was formed in the ring-shaped magnetic core, which allowed to obtain the closed magnetic circuit within the material and avoid the influence of the demagnetization effect. The prepared core is presented in Fig. 1. The Fig. 1. also schematically presents the methodology of application of compressive force to the core. The force is parallel to the axis of the core and perpendicular to the direction of the magnetizing field. The Tab. 1 presents geometrical dimensions of the prepared sample: outer diameter D, inner diameter d, thickness h, effective magnetic flow path within the sample le and effective cross-sectional area S_e .

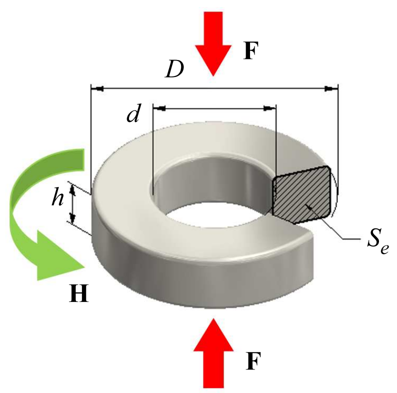

Fig. 1. Investigated ring core sample, H – magnetizing field, F – applied compressive force

Table 1. Geometrical parameters of the investigated ring core

Dimension	Unit	Value
D	mm	26.0
D	mm	16.0
h	mm	15.0
l_e	mm	65.9
S_e	mm^2	75.5

The core was equipped with the set of nonmagnetic backings with special grooves allowing to make windings necessary for magnetic measurements as well as to obtain nearly uniform distribution of applied stress. Two sets of windings were made in order to allow measurement of magnetic characteristics of the material: 5 turns of magnetizing winding and 50 turns of sensing winding.

4 Measurement setup

The measurement setup utilized during the experiment is schematically presented in Fig. 2. Measurement system is controlled by the PC with Data Acquisition Card (DAQ) installed. The voltage waveform generator produces sinusoidal waveform of frequency 1.0 Hz, which is then converted into current waveform by the voltage-current converter (voltage controlled bipolar current source). The generated current is proportional to the magnetizing field produced by the magnetizing winding driven by the current waveform. As a result of the magnetizing field acting on the sample, the voltage is induced in the sensing winding, which is amplified and send to the fluxmeter, which measures values of the magnetic flux density by integrating the induced voltage, as the dependence between magnetic flux density and induced voltage is described with the differential equation. Special program installed on the PC collects the measurement data (values of magnetizing field and magnetic flux density) and plots the graphs presenting magnetic hysteresis loops.

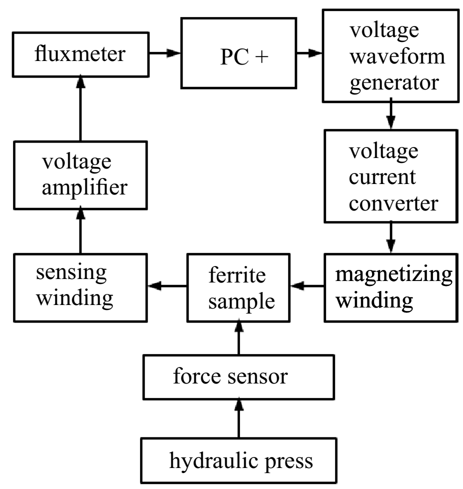

Fig. 2. Schematic block diagram of the measurement system

Compressive stress acting on the investigated sample is generated by the oil hydraulic press. Actual value of applied compressive force is measured with the strain gauge force sensor. Values of stress in the sample are calculated in relation to the surface are of the stressed core.

5 Measurement results and modelling

During the performed investigation, the Ni-Zn ferrite ring sample was subjected to the compressive stress σ from 0 MPa to 20 MPa with the step 2 MPa. For each stress the family of 16 hysteresis loops was measured within the range of magnetizing field amplitude from 2.5 A/m to 10.0 A/m. Both stress and magnetizing filed were applied in the increasing way.

Figure 3 presents the family of selected Rayleigh hysteresis loops measured for different values of applied compressive stress and constant value of magnetizing field amplitude $H_m = 6$ A/m. As it can be observed, the applied stress strongly affects the hysteresis loop and its parameters. With the increase of stress, significant decrease of the maximum magnetic flux density B_m is clearly observable. Also magnetic remanence and coercive field are

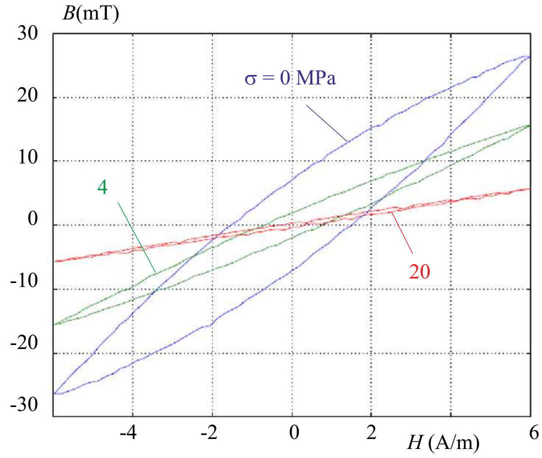

Fig. 3. Selected Rayleigh hysteresis loops of the investigated Ni-Zn ferrite under the influence of compressive stress σ (H_m = 6 A/m)

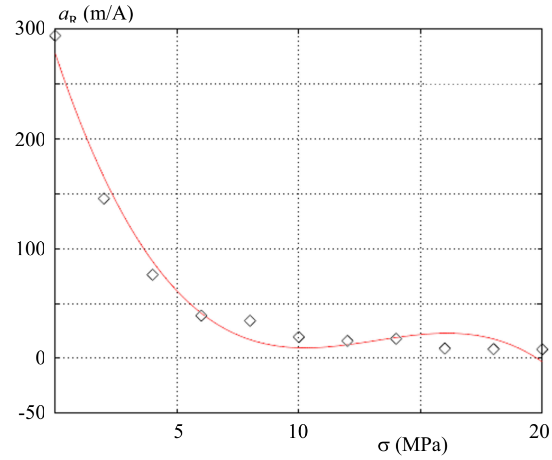

Fig. 5. Dependence of the Rayleigh coefficient α_R on compressive stress σs for investigated Ni-Zn ferrite: $y = -0.134x^3 + 5.301x^2 - 66.409x + 277.662$, $R^2 = 0.9799$

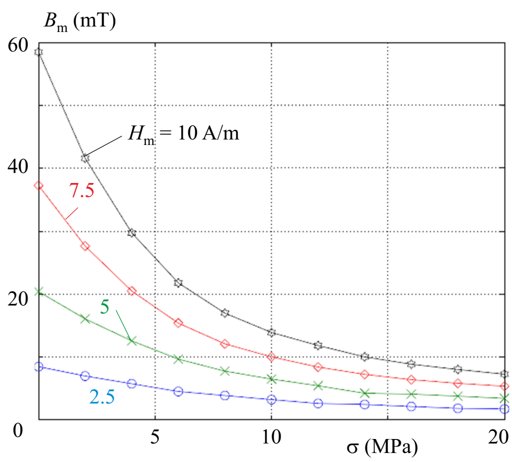

Fig. 4. Dependence of the maximum magnetic flux density B_m on the applied compressive stress s for selected values of magnetizing field amplitude H_m

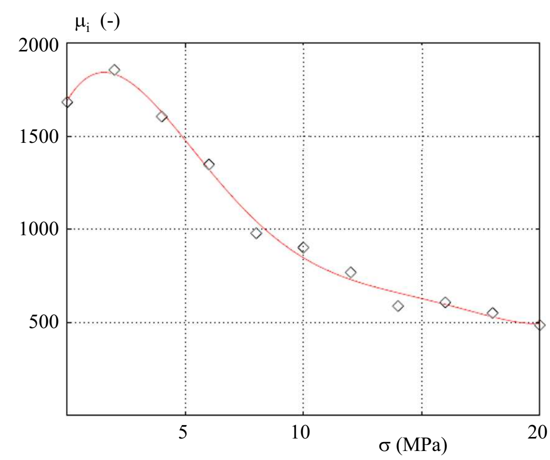

Fig. 6. The compressive stress σ dependence of initial relative magnetic permeability μ_i of investigated Ni-Zn ferrite: $y = 0.007x^5 0.042x^4 + 9.378x^3 88.745x^2 + 21.48x + 1689.3$, $R^2 = 0.9929$

rapidly decreasing, which all results in significant decrease of the surface area of the Rayleigh hysteresis loop.

In Fig. 4. the dependence of maximum magnetic flux density B_m on the applied compressive stress σ for several selected values of magnetizing field amplitude H_m is presented. It is clearly visible, that regardless of the magnetizing field value the characteristics are similar. The maximum value of B_m is seen for the unloaded sample. Then, with the increase of the value of applied stress σ, the monotonic decrease of the B_m values is occurring. The Villari reversal point is not observable unlike in classical Villari effect. It is the result of negative value of the product of saturation magnetostriction coefficient $\lambda_s > 0$ and applied compressive stress $\sigma < 0$ (compressive stress is traditionally considered as negative): $\lambda_s \sigma < 0$. The Villari point occurs only for positive value of product $\lambda_s \sigma$. From the point of view of sensor application, it is very favorable situation, as it allows to clearly connect the certain value of B_m with certain value of stress σ . There are no points that for certain magnetic flux density B_m can be characterized by two different value of stress σ.

On the basis of performed measurements, the values of material coefficients were determined for each value of applied stress. Figure 5 presents the dependence of Rayleigh coefficient α_R on the compressive stress σ, while Fig. 6 presents similar characteristic for initial relative magnetic permeability μ_i. Both characteristics were fitted with polynomial curves of higher degrees. Each dependence was fitted with the polynomial of the lowest possible degree giving satisfying value of the R^2 determination coefficient. In case of Rayleigh coefficient α_R, the dependence on the compressive stress can be approximated with the equation

$$\alpha_R(\sigma) = -0.134\sigma^3 + 5.301\sigma^2 \\ -66.409\sigma + 277.662 \tag{3}$$

The dependence between initial relative magnetic permeability μ_i and compressive stress σ is approximated with the equation

$$\mu_i(\sigma) = 0.007\sigma^5 - 0.042\sigma^4 + 9.378\sigma^3 \\ -88.745\sigma^2 + 21.48\sigma + 1689.3 \tag{4}$$

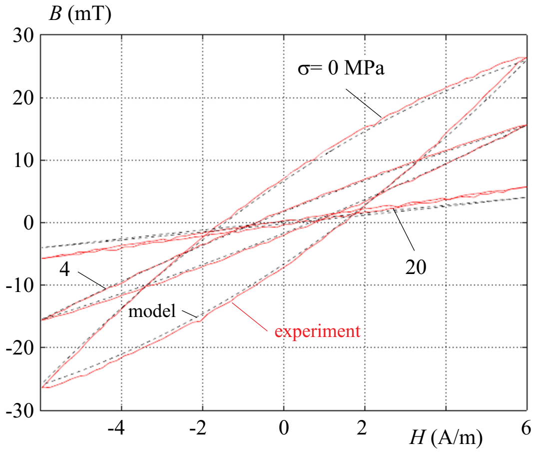

Fig. 7. Measured Rayleigh hysteresis loops and the results of modellingin sample of investigated Ni-Zn ferrite material($H_m = 6.0$ a/m); with coefficients R^2: 0.9988, 0.9993, 0.9109 for σ: 0, 4, 20 MPa

The polynomials were chosen in order to obtain maximum simplicity of the calculations, as they are the most natural and simple functions for computational machines.

Equations (3) and (4) combined with Rayleigh equations (1) and (2) can be utilized as very simplified mathematical model of magnetoelastic effect in Rayleigh region for technical and engineering applications. The equations allow to simulate the shape and parameters of the Rayleigh hysteresis loop for the given value of applied compressive stress and amplitude of magnetizing field H_m.

In order to validate the correctness of the presented model, second identical sample of the investigated Ni-Zn ferrite was prepared and measured at magnetizing field amplitude $H_m = 6.0$ A/m and several values of compressive stress σ . The experimental results were compared with the results of modelling, which is presented in Fig. 7. As it can be observed, there is a high correlation between experimental and modelling results, which is confirmed by the high values of R^2 determination coefficient.

6 Conclusions

For the first time the dependence of initial relative magnetic permeability and Rayleigh coefficient on the compressive stress in axially stressed ferrite core was determined. The obtained results indicate the strong correlation between magnetic properties of the investigated material and applied compressive stress. Moreover, the obtained dependence between maximum magnetic flux density and stress is monotonic, which allows to clearly determine the value of stress acting on the core on the basis of magnetic flux density measurement. Thus it can be stated, that investigated Ni-Zn ferrite material can be utilized in development of magnetoelastic stress and force sensor.

During the performed experiment, simplified mathematical model of the investigated phenomenon, based on the Rayleigh law of magnetization and polynomial equations, was developed. The correctness of the model was validated by comparison of the modelling results with the experimental data obtained with the second sample of the investigated material. The model works properly, which is confirmed by the obtained high values of the R^2 determination coefficient. Proposed model does not consider physical phenomenon occurring in the materials structure. However, it works correctly and is simple enough to be utilized in technical applications, where reduction of complexity of calculations is more important than consideration of physical processes within the structure of the material.

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