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# Investigation of Magnetoelastic Properties of $Ni_{0.36}Zn_{0.64}Fe_2O_4$ Ferrite Material under Low Magnetizing Fields Corresponding to Rayleigh Region

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The following paper presents original results of study on the magnetoelastic properties of Ni–Zn (nickel–zinc) ferrite material under low magnetizing fields, corresponding to the so-called Rayleigh region. The investigated $Ni_{0.36}Zn_{0.64}Fe_2O_4$ material was formed into frame-shape sample allowing to obtain uniform stress distribution. Special digitally controlled measurement system was utilized to perform investigation. Obtained results are presented in the paper. On the basis of them mathematical description of magnetoelastic effect in investigated material was developed as an extend of the Rayleigh model of magnetic hysteresis. Comparison of the experimental and modeling results indicates that the developed model is correct.

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## 1. Introduction

Ferrites, ceramic materials composed of iron oxide ($Fe_2O_3$) and one or more metallic elements, are one of the most important groups of magnetic materials [1, 2]. Ferrites are classified as ferrimagnetics. Their chemical composition results in double crystal lattice structure composed of atoms of opposite magnetic moments. Atomic magnetic moments in both crystal lattices are not equal and do not totally compensate each other, so material exhibits spontaneous magnetization.

Magnetoelastic Villari effect is a physical phenomenon involving change of magnetic properties of the material under the influence of mechanical stress [3]. It was previously reported that many ferrite materials exhibit strong magnetoelastic properties [4, 5]. However, most of the recent studies was performed for high amplitudes of magnetizing field. The purpose of the following paper is to present original results of investigation on magnetoelastic properties of soft ferrite material in low magnetizing fields corresponding to the so-called Rayleigh region.

## 2. Rayleigh model of hysteresis

The Rayleigh model of hysteresis was the first historical attempt to develop mathematical description of magnetic hysteresis phenomenon. It assumes that magnetizing field dependence of magnetization and magnetic flux density can be described with second order polynomial equation known as the Rayleigh law [6]:

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

where $B$ is magnetic flux density, $H$ is magnetizing field and $\mu_0$ is magnetic permeability of free space. Rayleigh proposed two material constants as the coefficients of the equation: initial magnetic permeability $\mu_i$ and so-called Rayleigh coefficient $\alpha_R$. On the basis of the Rayleigh law it is possible to determine equation of two parabolic curves being approximation of the two branches of hysteresis loop [7]:

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

where $H_m$ is amplitude of magnetizing field. Intersection points of the parabolic curves are vertices of the modelled hysteresis loop.

Such model of hysteresis is very simplified and is not satisfactory for modeling hysteresis phenomenon in high magnetizing fields. However, the Rayleigh law is a very good approximation of hysteresis loop for the region of low magnetizing fields, lower than saturation coercive field, which is known as the Rayleigh region. For such fields, hysteresis loop takes lenticular shape, which is perfectly represented by two intersecting parabolic curves.

## 3. Investigated material

Object of the performed investigation was Ni–Zn ferrite material of chemical composition $Ni_{0.36}Zn_{0.64}Fe_2O_4$. It is a soft ferrite utilized in magnetic recordings. Investigated material was characterized by average density value of 5.20 mg/mm$^3$ and saturation magnetostriction coefficient $\lambda_s = -5$ $\mu$m/m. For the investigation, material was formed into frame-shaped sample presented in Fig. 1. Cross-sectional area of the columns of the sample is 180 mm$^2$.

On the columns of the sample 20 turns of magnetizing winding and 50 turns of sensing winding were made in

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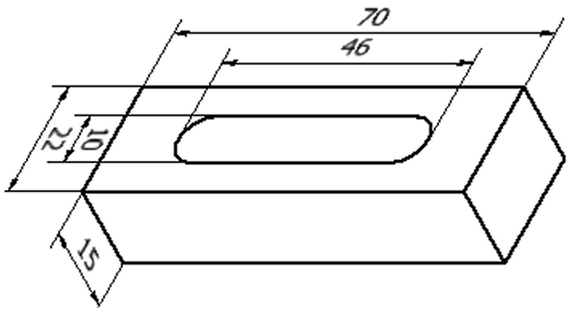


Fig. 1. Outline of the frame-shaped sample of $Ni_{0.36}Zn_{0.64}Fe_2O_4$ ferrite material (all dimensions in mm).

order to allow measurement of magnetic characteristics of the material.

## 4. Measurement setup

For the purpose of the performed investigation digitally controlled measurement system was developed. Schematic block diagram of the setup is presented in Fig. 2.

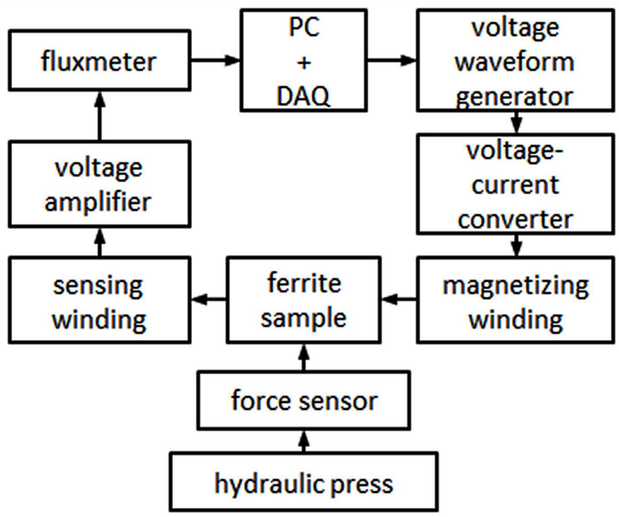


Fig. 2. Schematic block diagram of the measurement setup.

The oil hydraulic press was utilized during the performed investigation as a source of mechanical stress. Force generated by the press was measured with strain gauge force sensor.

Measurement system was controlled by PC with data acquisition card (DAQ) installed. Magnetizing waveform was generated from the sinusoidal voltage waveform generator and converted into current waveform driving magnetizing winding with voltage–current converter. Voltage induced in the sensing winding was amplified and values of the magnetic flux density were measured with the fluxmeter and transferred to the PC.

## 5. Experimental results

During the investigation the sample was subjected to the compressive stress $\sigma_c$ within the range from 0 MPa to 60 MPa. Stress was applied incrementally. For each value of compressive stress $\sigma_c$, commutation curve was measured for the maximum value of magnetizing field equal to 5 A/m. Results of the investigation are presented in Fig. 3.

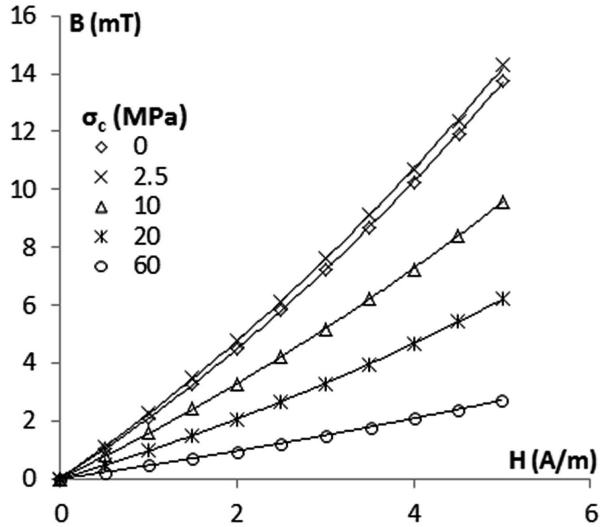


Fig. 3. Selected commutation curves under the influence of compressive stress $\sigma_c$ for $Ni_{0.36}Zn_{0.64}Fe_2O_4$ ferrite material.

Each commutation curve obtained during the investigation was fitted with second order polynomial curve. Comparison of resulting equations with Eq. (1) allowed to determine values of initial magnetic permeability $\mu_i$ and the Rayleigh coefficient $\alpha_R$ for each value of applied compressive stress $\sigma_c$. As a result, characteristics of stress $\sigma_c$ dependence of these two material parameters were obtained, which can be seen in Fig. 4.

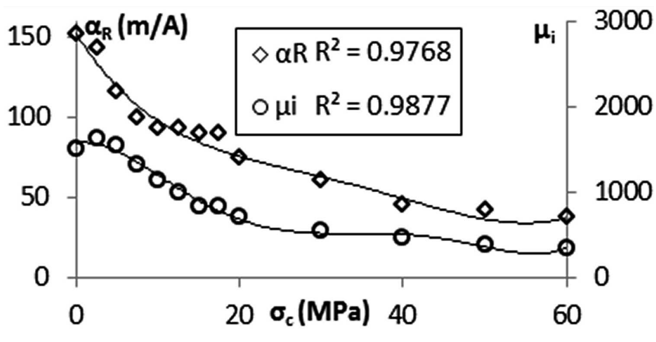


Fig. 4. The compressive stress $\sigma_c$ dependence of Rayleigh coefficient $\alpha_R$ and initial permeability $\mu_i$ for $Ni_{0.36}Zn_{0.64}Fe_2O_4$ ferrite material.

Initial magnetic permeability reaches its maximum value for the stress about 2.5 MPa. This value of compressive stress is corresponding to the Villari point, which is maximum value of magnetic flux density $B$ on the $B(\sigma_c)$ characteristic [4].

Both obtained characteristics were fitted with polynomial curves of higher orders. It allowed to determine equations describing compressive stress $\sigma_c$ dependence of the Rayleigh coefficient $\alpha_\mathrm{R}$:

$$\alpha_\mathrm{R}(\sigma_c) = 5 \times 10^{-5} \times \sigma_c^4 - 0.0067 \times \sigma_c^3 + 0.3245 \times \sigma_c^2 - 8.042 \times \sigma_c + 152 \quad (3)$$

and initial magnetic permeability $\mu_i$:

$$\mu_i(\sigma_c) = 5 \times 10^{-5}\sigma_c^5 - 0.0082 \times \sigma_c^4 + 0.4424 \times \sigma_c^3 - 9.0626 \times \sigma_c^2 + 16.734 \times \sigma_c + 1572. \quad (4)$$

The values of $R^2$ determination coefficients for each curve are presented in Fig. 4. This equations, together with Eq. (2) are the model of the Rayleigh hysteresis loop under the influence of compressive stress for $Ni_{0.36}Zn_{0.64}Fe_2O_4$ ferrite material and allow to model the shape of hysteresis loop for given value of compressive stress $\sigma_c$.

For validation of the presented model, second sample made of the same material was prepared and investigated. Results obtained for this validation sample were compared with the modeled Rayleigh hysteresis loops for different validation points of compressive stress $\sigma_c$ value, which is presented in Fig. 5.

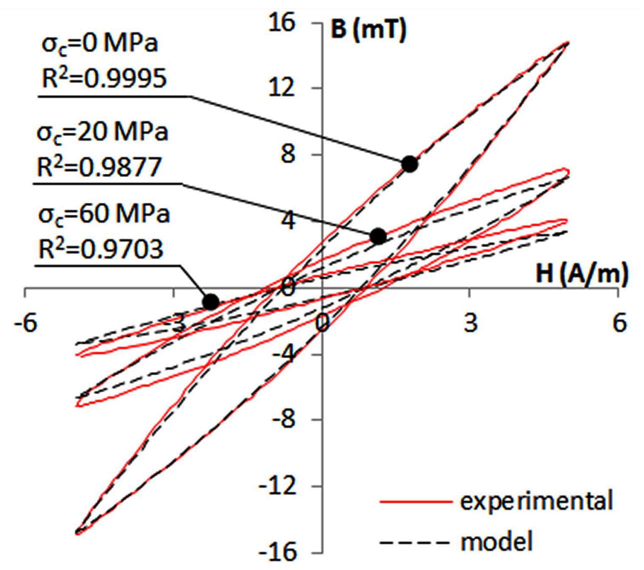


Fig. 5. Results of validation of developed model for different values of compressive stress $\sigma_c$ and constant value of magnetizing field $H_m = 5$ A/m for $Ni_{0.36}Zn_{0.64}Fe_2O_4$ ferrite material.

As it can be seen, for each value of compressive stress $\sigma_c$ correlation between experimental and calculated data is high, especially for low values of stress. In every validation point, determination coefficient $R^2$ was calculated. Obtained values are higher than 0.97 which indicate high correctness of the developed model.

## 6. Conclusion

Magnetoelastic characteristics of $Ni_{0.36}Zn_{0.64}Fe_2O_4$ ferrite material presented in the paper indicates that there is strong correlation between magnetic parameters of the material and applied mechanical stress. After analysis of the measurement results, simplified model of this correlation was developed based on the Rayleigh hysteresis model. This model allows to determine the approximate shape of the hysteresis loop for given value of applied compressive stress in the region of low magnetizing fields (the Rayleigh region). Calculated values of determination coefficient $R^2$ indicate that developed model exhibits high correlation with measurement data.

Presented model is just simplified mathematical description of magnetoelastic effect in the Rayleigh region for investigated $Ni_{0.36}Zn_{0.64}Fe_2O_4$ ferrite material. It could be used in some simple technical applications like SPICE modeling of the inductive elements. However, further investigation is necessary to develop complex model involving physical phenomenon occurring in the crystalline structure of the material during the magnetization process.

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