MODELLING MAGNETOELASTIC CHARACTERISTICS OF MANGANESE-ZINC FERRITE MATERIAL IN RAYLEIGH REGION

***Maciej Kachniarz*[1]*, Adam Bieńkowski*[1]*, Roman Szewczyk*[1]**

[1]*Institute of Metrology and Biomedical Engineering, Warsaw University of Technology, ul. św. Andrzeja Boboli 8, 02-525 Warsaw, Poland*

E-mail: m.kachniarz@mchtr.pw.edu.pl

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1. Introduction

Ferrite magnetic materials have a wide range of applications and are present in many electronic devices. The main field of utilization of soft ferrite materials are magnetic cores in transformers, filters, chokes and other inductive components used in electronic industry [1]. One of the most important groups of ferrite materials are manganese-zinc (Mn-Zn) ferrites characterized by high values of the relative initial magnetic permeability.

It was previously reported that Mn-Zn ferritesexhibit strong magnetoelastic properties [2]. Occurrence of the magnetoelastic Villari effect in ferrite magnetic core may be caused not only by external forces, but also by mechanical stresses in material resulting from heat treatment of the core during manufacturing process. Villari effect causes changes in magnetic properties of the material which may result in incorrect working of inductive element with magnetic core having internal stresses. Because of this there is a great need to develop mathematical model describing the influence of mechanical stress on the magnetic properties of ferrite materials. Such models were elaborated before [3, 4], but they were always focused on magnetization process near saturation region with high magnetizing field, while most of modern inductive components are working with low magnetizing fields in so called Rayleigh region [5].

Magnetoelastic Villari effect is also observable in Rayleigh region [6]. Previously some attempts were to adapt Jiles-Atherton extended model for Rayleigh region [7]. However, obtained model is complex and hard to implement in technical applications. Moreover, there were significantly differences between results of modelling and experimental data. So there is still need to develop simpler and easier to apply model for practical use.

The paper presents the original methodology and results of modelling magnetoelastic effect in Rayleigh region for Mn-Zn ferrite material of chemical composition $Mn_{0.58}Zn_{0.36}Fe_{2.06}O_4$. The methodology is based in experimental results, so also measurement setup and methodology are described. On the basis of measurement results simple mathematical model is developed allowing to model the shape of hysteresis loop in Rayleigh region depending on the mechanical stress in the material.

2. Rayleigh region

Rayleigh region is the first part of the initial magnetization curve, where the dominant mechanism of magnetization are reversible elastic deflections of the domain walls, but also irreversible translations of the domain walls are occurring, which allows to observe magnetic hysteresis phenomenon. The initial magnetization curve in Rayleigh region is described by the second order equation known as Rayleigh law [8] with to material parameters: initial relative permeability μ_i and so called Rayleigh coefficient α_R:

$$B(H) = \mu_0 \mu_i H + \mu_0 \alpha_R H^2 \quad (1)$$

where B is magnetic flux density in the material, H is magnetizing field and μ_0 is vacuum magnetic permeability.Hysteresis loop in Rayleigh region (known as Rayleigh hysteresis loop) has lenticular shape unlike hysteresis loop in near saturation region. Both decreasing branch and increasing branchare parabolic curves, which allow to describe the Rayleigh hysteresis loop with the system of two equations:

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

$$B(H) = \mu_0[(\mu_i + \alpha_R H_m)H - \frac{\alpha_R}{2}(H_m^2 - H^2)] \quad (3)$$

where H_m is amplitude of magnetizing field. Eq.(2) refers to decreasing branch of Rayleigh hysteresis loop and Eq.(3) describes increasing branch.

3. Measurement methodology

Investigated Mn-Zn ferrite material of chemical composition$Mn_{0.58}Zn_{0.36}Fe_{2.06}O_4$ was subjected to compressive stress $\sigma_c$in the range from 0 MPa to 100 MPa. Material was formed into frame-shaped samples allowing to apply compressive stress. The frame-shaped sample used for investigation is presented in Fig. 1. On the columns of the sample magnetizing and sensing winding were made, allowing to measure magnetic characteristics of the material.

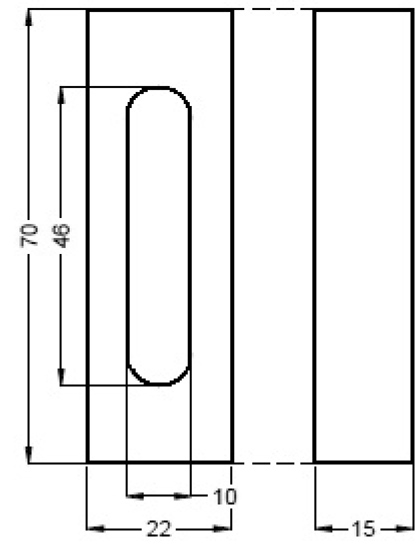

Fig.1:*Framed-shaped sample of investigated material used for experiment.*

For the investigation, special measurement system was developed presented in Fig. 2. The oil hydraulic press is utilized to apply mechanical compressive stressσ_c to the material sample placed between two ball joints providing symmetrical application of the stress. The value of force applied with the press is measured with force sensor and calculated to the stress value. Sinusoidal magnetizing field is generated with digitally controlled voltage sine wave generator. Voltage waveform from the generator is sent to voltage-current converter in order to obtain magnetizing current waveform which drives magnetizing winding. Voltage induced in sensing winding is amplified and integrated to obtain values proportional to the magnetic flux density B in the material. Both magnetizing and integrated sensing waveform are collected with digital oscilloscope and send to the PC, where measurement data are processed. Special program installed on the computer calculates values of magnetizing field H and magnetic flux density B and draws a graph of Rayleigh hysteresis loop.

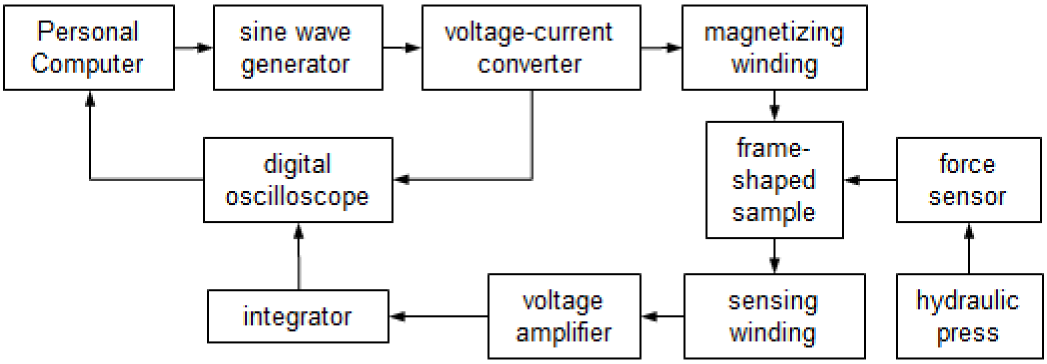

Fig.2:*Schematic block diagram of the measurement system.*

4. Experimental results and modelling

For each value of the applied stress σ_c, Rayleigh hysteresis loop were measured for several values of the amplitude of magnetizing field in the range from 0 A/m to 25 A/m. As a result of the measurement, several magnetoelastic characteristics presenting dependence of the maximum magnetic flux density B_m to the magnetizing field amplitude H_m, which are presented in Fig. 3.

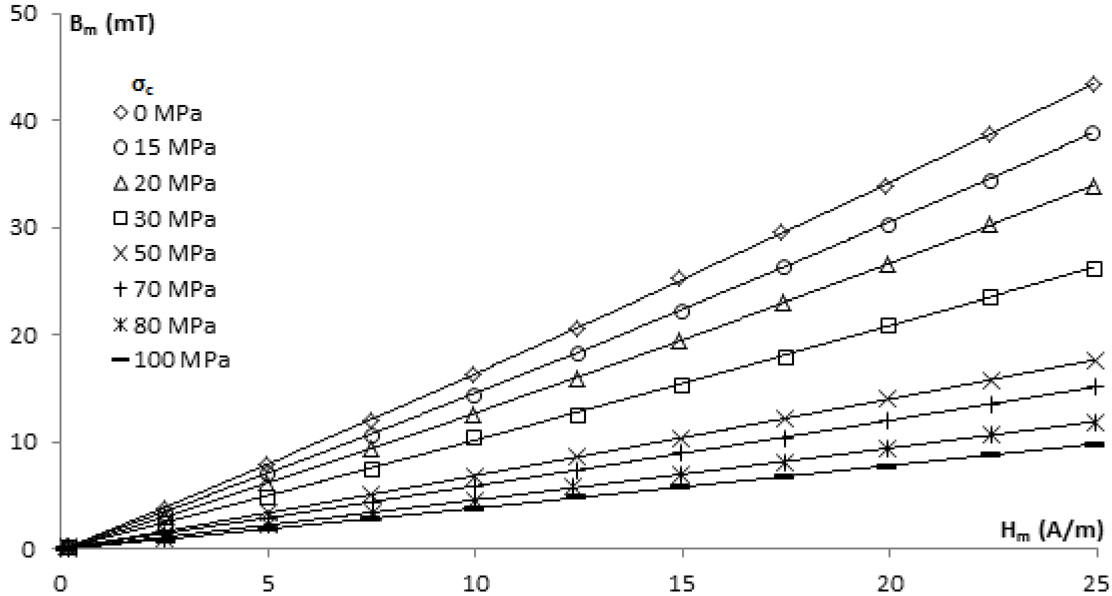

Fig.3: *$B_m(H_m)$ characteristics of investigated $Mn_{0.58}Zn_{0.36}Fe_{2.06}O_4$ material for different values of compressive stress σ_c fitted with second order curves.*

All obtained $B_m(H_m)$ characteristics for different values of the compressive stresses were fitted with second order curves according to Eq.(1). For each second order equation obtained as a result of fitting operation values of two coefficients: initial relative permeability μ_i and Rayleigh coefficient α_R were calculated for given value of compressive stress σ_c. On the basis of the calculated values, characteristic of initial relative permeability μ_i and Rayleigh coefficient α_R depending on the compressive stress σ_c were determined, which are presented in Fig. 4.

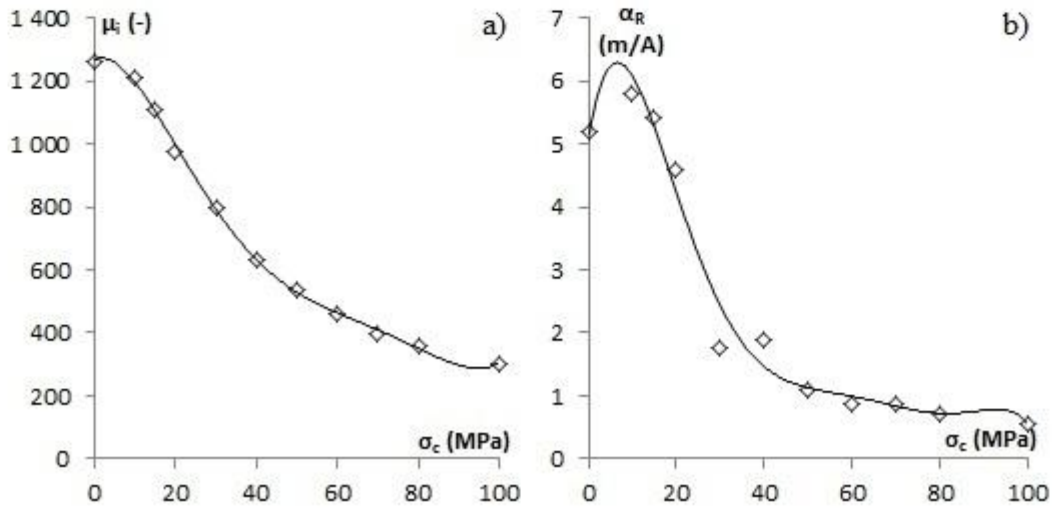

Fig.4: *a) The compressive stress σ_c dependence of: a) initial magnetic permeability μ_i, b) Rayleigh coefficient α_R of the investigated $Mn_{0.58}Zn_{0.36}Fe_{2.06}O_4$ ferrite material.*

Both presented characteristics were fitted with polynomial curves of higher orders. This allows to determine equations describing changes of initial relative permeability μ_i and Rayleigh coefficient $\alpha_R$depending on the value of applied compressive stress σ_c. Compressive stress dependence of the ininitial relative permeability μ_i is described with fifth order equation:

$$\mu_i(\sigma_c) = 1.86 \cdot 10^{-6}\sigma_c^5 - 5.04 \cdot 10^{-4}\sigma_c^4 + 4.84 \cdot 10^{-2}\sigma_c^3 - 1.83\sigma_c^2 + 7.51\sigma_c + 1270 \quad (4)$$

while changes of Rayleigh coefficient α_R depending on compressive stress σ_c is described by the sixth order equation:

$$\alpha_R(\sigma_c) = -5.36 \cdot 10^{-10}\sigma_c^6 + 1.79 \cdot 10^{-7}\sigma_c^5 - 2.34 \cdot 10^{-5}\sigma_c^4 + \\ 1{,}48 \cdot 10^{-3}\sigma_c^3 - 4.45 \cdot 10^{-2}\sigma_c^2 + 0{,}41\sigma_c + 5.16 \quad (5)$$

Obtained equations allow to calculate values of initial relative permeability μ_i and Rayleigh coefficient α_R for given value of applied compressivestress σ_c. After substituting this values to Eq.(2) and Eq.(3) it is possible to model shape of the Rayleigh hysteresis loop for given value of applied compressivestress σ_c. On the basis of developed model, family of Rayleigh hysteresis loops for several values of compressivestress σ_c was drawn, which is presented in Fig. 5. As it can be seen, there is a strong correlation between compressive stress σ_c applied to the material and its magnetic properties. For higher values of compressive stress, maximum magnetic flux density is much smaller than for low values. Also values of coercive field H_c and remanenceB_r are decreasing with growth of the stress values. This results in much smaller surface area of the Rayleigh hysteresis loop with high value of applied compressive stress.

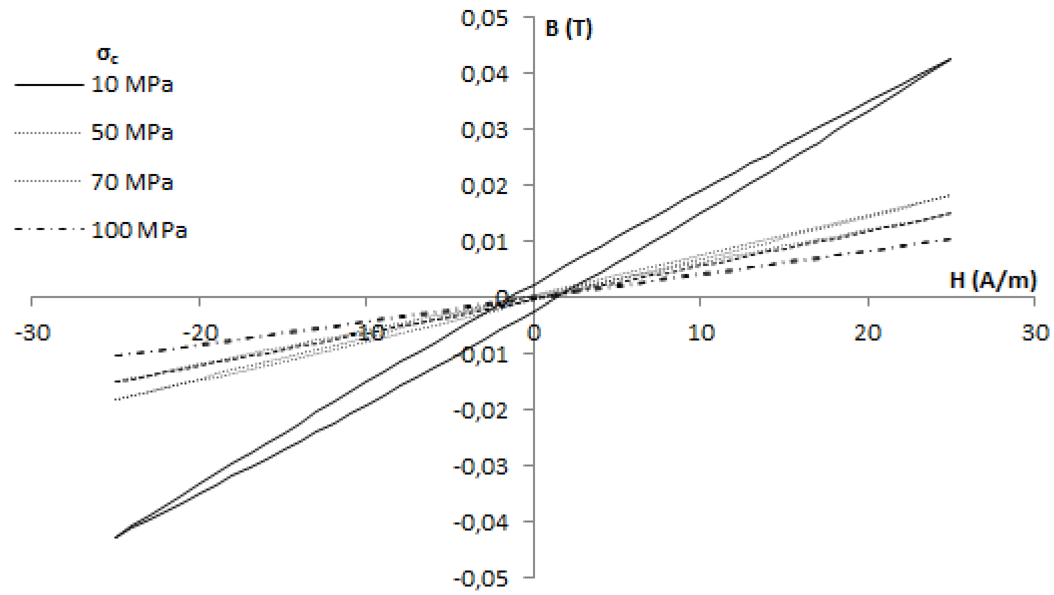

Fig.5:*Modelled family of Rayleigh hysteresis loops for amplitude of magnetizing field* H_m = *25 A/m for investigated* $Mn_{0.58}Zn_{0.36}Fe_{2.06}O_4$*material.*

5. Conclusions

Performed measurements and calculations allowed to obtain the system of equations allowing to model values of basic parameters of Rayleigh hysteresis loop (initial relative permeability μ_i and Rayleigh coefficient α_R) depending on the value of applied compressive stress σ_c. On the basis of the parameters calculated for given value of compressive stress, there is a possibility to model shape of the Rayleigh hysteresis loop.

Presented model is simple and can be easily used in practical applications like Spice software for modelling parameters of electronic elements including inductive components. This would be very helpful during the process of design of electronic circuits utilizing inductive components with ferrite cores.

References:

[1] R.C. O'Handley: Modern Magnetic Materials: Principles and Applications, John Wiley & Sons, New York USA (2000).

[2] A. Bieńkowski: *Journal of Magnetism and Magnetic Materials*, **215-216**, 231 (2000).

[3] R. Szewczyk: *PRAMANA – Journal of Physics*, **67**, 1165 (2006).

[4] D. Jackiewicz, R. Szewczyk, J. Salach, A. Bieńkowski: *Acta Physica Polonica A*, **126**, 392 (2014).

[5] L. Nowák, J. Kováč: *Acta Physica Polonica A*, **126**, 126 (2014).

[6] R.R. Birss: *IEEE Transactions on Magnetics*, **MAG-7**, 113 (1971).

[7] L. Li, D.C. Jiles: *IEEE Transactions on Magnetics*, **39**, 3037 (2003).

[8] D.C. Jiles: Introduction to Magnetism and Magnetic Materials, CHAPMAN&HALL, London UK (1998).