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MODELING THE SOFT MAGNETIC MATERIALS WITH HIGH PERMEABILITY IN A LARGE RANGE OF FREQUENCIES

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Materialele magnetice moi cu permeabilitate magnetică ridicată sunt utilizate în dispozitive electromagnetice ce funcţionează într-o gamă largă de frecvenţe. De aceea, este importantă cunoaşterea comportamentului acestor materiale de la curent continuu până la frecvenţe de ordinul MHz. Lucrarea de faţă îşi propune abordarea problemei modelării comportamentului materialelor magnetice moi la frecvenţe ridicate, urmărind reproductibilitatea ciclului de histerezis şi obţinerea unor valori cât apropiate a pierderilor prin histerezis de valorile experimentale.

Soft magnetic materials with high magnetic permeability are common used in electromagnetic devices working in a large range of frequencies. Therefore, it is important to know the behavior of these materials from DC to MHz frequencies. The aim of this paper is to model the behavior of the soft magnetic materials in high frequencies to ensure the reproducibility of the hysteresis loop and to obtain values of the hysteresis losses closed to the experimentally measured ones.

Keywords: soft magnetic materials, hysteresis loop, hysteresis losses, magnetic material modeling, high permeability, Rayleigh model

1. Introduction

The most important features of a soft magnetic material are very low magnetocrystalline anisotropy and a very high permeability [1] because these properties ensure low energy losses and their widespread use in devices working in high frequencies. Almost all the magnetic ordered materials have a nonlinear and hysteretic behavior [2]. Usually, the losses per cycle are depending nonlinearly on the frequency, and the response to a sinusoidal field excitation H, produced, generally, a deformed waveform of the flux density B [3].

Experimental results obtained on this kind of materials were previous presented [4]. The aim of this paper is to provide a magnetic model to predict the behavior of these materials in high frequencies. The hysteresis loop of the same

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material measured on different frequencies is different. So the shape of the dynamic loops depends of the peak polarization, the frequency and the microstructure characteristics; the area of the loop, W is a non linear function of the frequency; the hysteresis loop area at zero frequency is not zero; this value represents the quasistatic losses (hysteresis losses).

2. Rayleigh model

In high frequencies the devices can't work at high values of the magnetic flux density, close to the saturation point and this was the reason why applied the Rayleigh model [5] to obtain the hysteresis loops at frequencies up to 5 MHz. This model describes the hysteresis loop in the domain of weak magnetic fields where the magnetic permeability is considered a linear function of magnetic field:

$$\mu = \mu_i + \nu H \tag{1}$$

where μ_i is the initial permeability (for $H = 0$) and υ is the Rayleigh coefficient. The magnetic flux density is a quadratic function of the magnetic field for the first magnetization curve:

$$B = \mu_i H + \upsilon H^2 \tag{2}$$

To describe the major loop, Rayleigh proposed a parabolic shape of the magnetic loops and considered that differential permeability in the tip points is the same with the initial permeability. The equation of the loop becomes:

$$B = \mu_m H \pm \frac{\upsilon\left(H_m^2 - H^2\right)}{2} \tag{3}$$

where

$$\mu_m = \mu_i + \upsilon H_m = \frac{B_m}{H_m} \tag{4}$$

is the magnetic permeability for $H = H_m$. The signs in the relation (3) correspond to the descending branch (+), respectively to the ascending one (-).

3. Experimental results

For each frequency a set of experimental data were used: coercive force (H_c), remanent flux density (B_r) and the parameters of the tip point of the major loop (H_m, B_m).

The model coefficients (μ_i, ν) can be determined from the above equations in particular points. In the remanent flux density point (0, B_r) the eq. (3) becomes:

$$B_r = \frac{\upsilon H_m^2}{2} \text{, and therefore, } \upsilon = \frac{2B_r}{H_m^2} \tag{5}$$

Also, from eq. (4) we can determine the initial permeability:

$$\mu_i = \mu_m - \upsilon H_m, \text{with } \mu_m = \frac{B_m}{H_m} \tag{6}$$

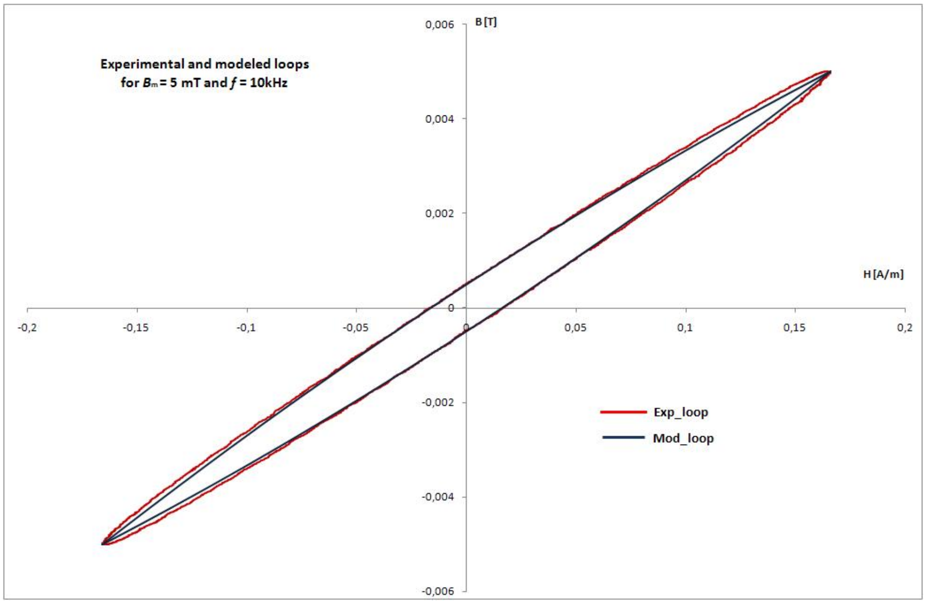

Fig.1. Experimental and modeled loops for B_m = 5 mT and f = 10 kHz

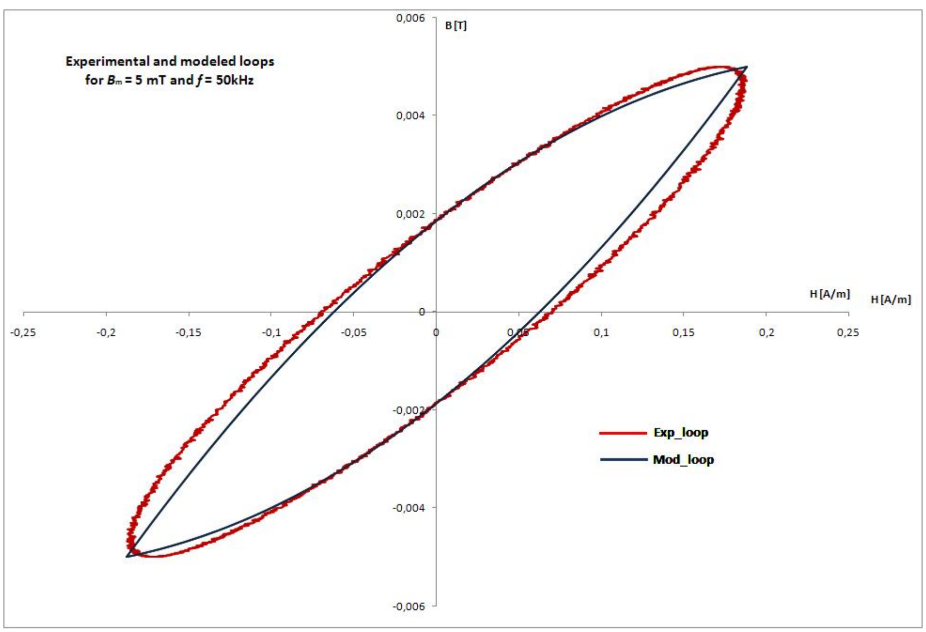

Fig.2. Experimental and modeled loops for B_m = 5 mT and f = 50 kHz

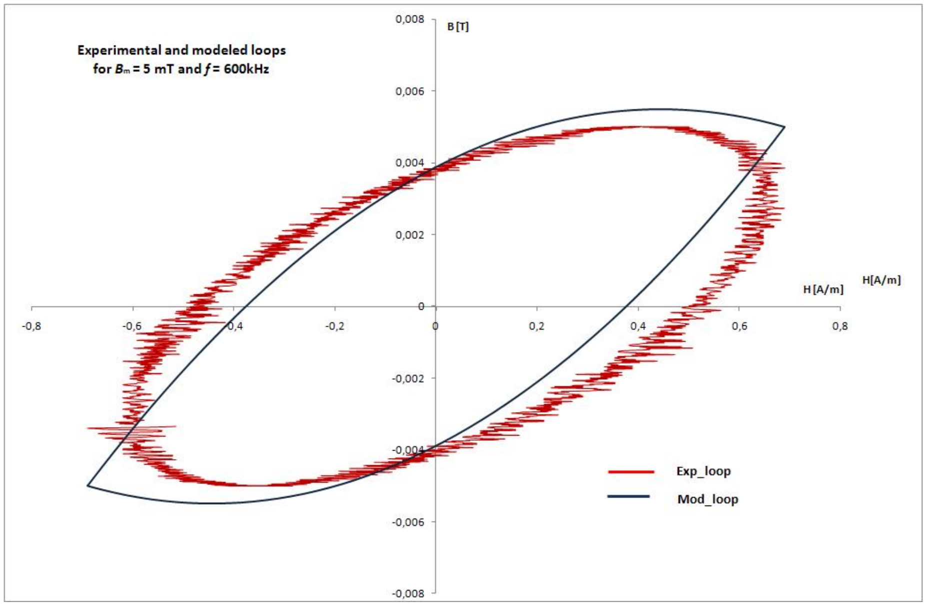

Fig.3. Experimental and modeled loops for B_{m} = 5 mT and f = 600 kHz

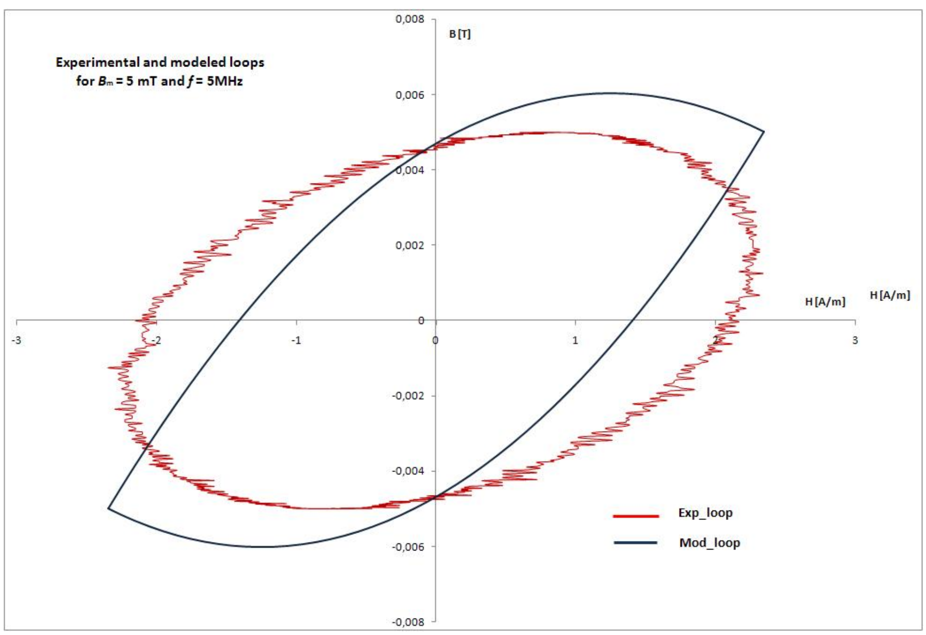

Fig.4. Experimental and modeled loops for B_{m} = 5 mT and f = 5 MHz

The experimental results and the modeled loops for the same sample of a commercial nanocrystalline ribbon, FINEMET-D [6], of the 19 μm thickness are presented in Figures 1 – 4. The maximum flux density is 5 mT for all frequencies (10 kHz, 50 kHz, 600 kHz, and 5 MHz).

The coercive force point is very different on the experimental and on the modeled loop, particularly in higher frequencies. A comparison between the experimental values (H_{c_exp}) and the modeled value obtained from the eq. (3) for $B = 0$ is presented in Table 1:

$$H_{c\_mod} = \sqrt{H_m^2 + \frac{\mu_m^2}{\upsilon^2}} - \frac{\mu_m}{\upsilon} \tag{7}$$

The relative error is:

$$\varepsilon_r = \frac{H_{c\_exp} - H_{c\_mod}}{H_{c\_exp}} \cdot 100[\%] \tag{8}$$

Table 1

Experimental and modeled results for the coercive field at B_m = 5 mT

f	10 kHz	50 kHz	600 kHz	5 MHz
H_{c_mod} [A/m]	0.0162710	0.0622884	0.3758171	1.406118
H_{c_exp} [A/m]	0.0167364	0.0690671	0.4909058	2.092842
ε_r [%]	2.78	9.81	23.44	32.81

The total losses per loop represent also an important data for the analysis of the behavior of the materials in high frequencies fields [4]. If on the sample is applied a sinusoidal magnetic field $H(t) = H_p \cos \omega t$, the magnetic flux density will be out of phase because of the eddy currents:

$$B(t) = B_p \cos(\omega t - \varphi) = B_p \cos\varphi \cos \omega t + B_p \sin\varphi \sin \omega t \tag{9}$$

The two components have different amplitudes, $B_1 = B_p \cos\varphi$ and $B_2 = B_p \sin\varphi$, and they are 90^0 phase-shifted. The second generates magnetic losses [3]. These terms also are associated with the real part (μ’) and the imaginary part (μ”) of the magnetic permeability. Total losses are dependent of the imaginary part of the permeability, because the angle φ is not too large, so the ‘*sin*’ function generates a more significant term:

$$P_{exp} = \pi \cdot H_p^2 \cdot \mu'' \tag{10}$$

The Rayleigh model offers a formula to calculate this parameter:

$$P_{his} = \oint_{loop} H \cdot dB = \frac{4}{3} \upsilon H_m^3 \tag{11}$$

The hysteresis loop has an elliptic shape, so the total losses are equal with the ellipse area (shown on the Figure 5) calculated with the equation:

$$P_{\text{elip}} = \pi \cdot a \cdot b = \pi \cdot \sqrt{H_{\text{m}}^2 + \text{B}_{\text{m}}^2} \cdot \frac{B_{\text{r}} \cdot H_{\text{c}}}{\sqrt{H_{\text{m}}^2 + \text{B}_{\text{m}}^2}} \tag{12}$$

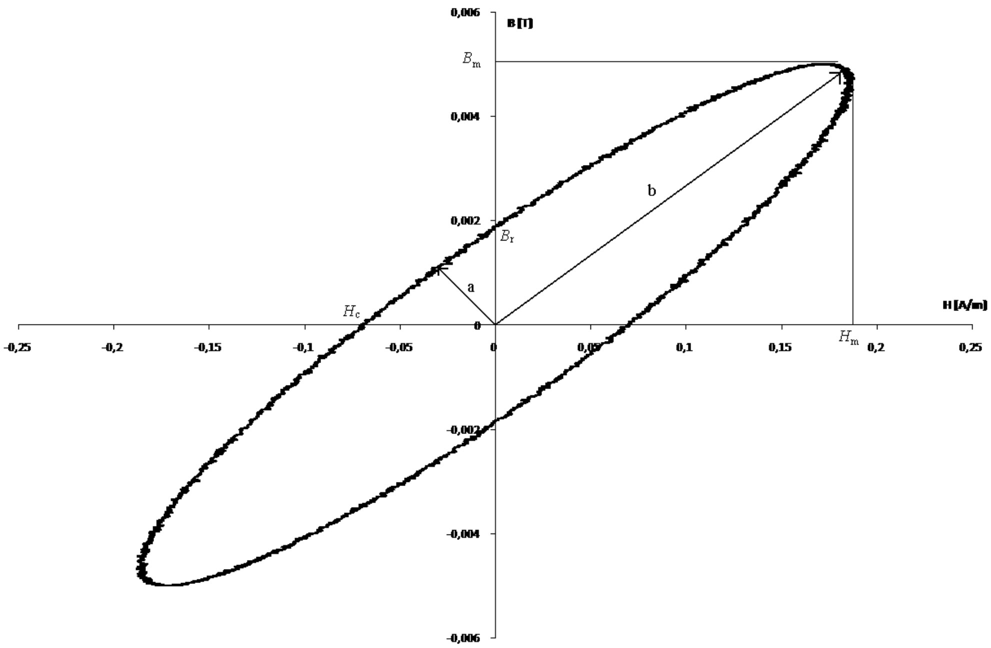

Fig.5. Elliptic loop used to calculate P_{elip}

It is interesting to compare the experimental values with the two values presented above, using relative errors (Table 2):

$$\varepsilon_1 = \left| \frac{P_{\text{his}} - P_{\text{exp}}}{P_{\text{exp}}} \right| \cdot 100[\%]$$
$$\varepsilon_2 = \left| \frac{P_{\text{elip}} - P_{\text{exp}}}{P_{\text{exp}}} \right| \cdot 100[\%] \tag{13}$$

Table 2

Experimental and modeled results for total losses at B_m = 5 mT

f	10 kHz	50 kHz	600 kHz	5 MHz
P_{his} [J/m^3]	2.19E-04	9.32E-04	7.14E-03	3.56E-02
P_{exp} [J/m^3]	2.58E-04	1.09E-03	7.76E-03	3.27E-02
P_{elip} [J/m^3]	2.58E-04	1.10E-03	8.41E-03	3.45E-02
ε_1 [%]	15.12%	14.50%	7.99%	8.87%
ε_2 [%]	0.00%	0.92%	8.38%	5.50%

For a better understanding of the model accuracy the same calculus was performed for higher values of the flux density B_m = 20 mT, and respectively B_m = 200 mT. The results are presented in Tables 3 - 6.

Table 3

Experimental and modeled results for the coercive field at B_m = 20 mT

f	10 kHz	50 kHz	600 kHz	5 MHz
$H_{c\ mod}$ [A/m]	0.0783	0.252486152	1.408006317	5.35840317
$H_{c\ exp}$ [A/m]	0.0790899	0.285676311	1.958261641	8.302904946
ε_r [%]	1.00	11.62	28.10	35.46

Table 4

Experimental and modeled results for the coercive field at B_m = 200 mT

f	10 kHz	50 kHz	600 kHz
$H_{c\ mod}$ [A/m]	0.881245213	2.626036832	13.85255618
$H_{c\ exp}$ [A/m]	0.897701326	2.883192646	21.54614814
ε_r [%]	1.83	8.92	35.71

Table 5

Experimental and modeled results for total losses at B_m = 20 mT

f	10 kHz	50 kHz	600 kHz	5 MHz
P_{his} [J/m^3]	4.24E-03	1.53E-02	1.08E-01	5.43E-01
P_{exp} [J/m^3]	4.92E-03	1.79E-02	1.24E-01	5.17E-01
P_{elip} [J/m^3]	4.96E-03	1.68E-02	1.03E-01	4.01E-01
ε_1 [%]	13.82%	14.53%	12.90%	5.03%
ε_2 [%]	0.81%	6.15%	16.94%	22.44%

Table 6

Experimental and modeled results for total losses at B_m = 200 mT

f	10 kHz	50 kHz	600 kHz
P_{his} [J/m^3]	4.81E-01	1.62	1.17E01
P_{exp} [J/m^3]	5.65E-01	1.82	1.38E01
P_{elip} [J/m^3]	5.61E-01	1.77	1.04E01
ε_1 [%]	14.87%	10.99%	15.22%
ε_2 [%]	0.71%	2.75%	24.64%

4. Conclusions

The paper presents an application of the Rayleigh model to soft magnetic materials used in a large range of frequencies. The nanocrystalline material is a sample of commercial FINEMET-D, of reduced thickness. This is a nanocrystalline material obtained by heat-treating an iron based amorphous alloy.

Cores made from this alloy and heat-treated to obtain quite square BH loops are useful to manufacture better magnetic amplifiers in switch-mode power supplies. These cores have low coercive field and low core losses, for a maximum saturation magnetization of about 1.20 – 1.23 T.

Due to the high frequency at which these devices are working, the applied field and the flux density are much lower than the saturation values and this is the reason way this model is appropriate to use. The observed differences are significant particularly for frequencies close to MHz, but they are admissible in the range of the kHz. The relative errors of the coercive force and the total losses are increasing with the frequency and the flux density.

From Table 2, 5 and 6 it can observe that the second error gave more precise results. This can be explained thru the fact that for frequencies lower than 100 kHz the hysteresis loop is closure in shape with an ellipse. For higher values of the frequencies the hysteresis loop tends to a more circular shape so the losses calculate with the Rayleigh equation gave more precise information.

The main contribution of this paper is to offer a mathematical model for hysteresis loops obtained in a various range of frequencies.

We conclude that the Rayleigh model can be applied with good results for frequencies up to 100 – 200 kHz and for low values of the flux density of 20 – 50 mT, representing less than 10% from the saturation value.

A future work can be done to improve this model in order to obtained better results at higher frequencies and flux density.

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