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Modeling of Thermal effects on Magnetic Hysteresis using the Jiles-Atherton Model

***Abstract**. The present paper deals with a temperature dependent modelling approach for the generation of hysteresis loops of ferromagnetic materials. The physical model is developed to study the effect of temperature on the magnetic hysteresis loop using JA model. The thermal effects were incorporated through temperature dependent hysteresis parameters of JA model. The temperature-dependent JA model was validated against measurements made on the ferrite material and the results of proposed model were in good agreement.*

***Streszczenie.** Zaprezentowano metodę modelowania pętli histerezy z uwzględnieniem wpływu temperatury. Do tego celu wykorzystano model Jiles-Atherton włączając do modelu parametry zależne od temperatury. Model sprawdzono na materiałach ferrytowych. (**Modelowanie wpływu temperatury na pętlę histerezy przy wykorzystaniu modelu Jlies-Atherton**)*

Keywords: Jiles-Atherton model, Magnetic hysteresis, Temperature, Modeling.
Słowa kluczowe: Model Jiles-Atherton, pętla histerezy.

1. Introduction

Magnetic hysteresis is encountered in the operation of most Electrical Engineering devices (motors, transformers, magnetic recording, and components for power electronics). The development of a model can accurately describe this cycle and its variation depending on the operating regime that is still an issue that inspires researchers.

Amongst these models, we find the Jile-Atherton model which is based on energy considerations, that is on the movement of Bloch walls within the material. Its inconvenience lies in the identification of parameters and especially in case of temperature change. All machines are electric seat Joule losses, hysteresis and eddy currents, making these devices heat up. For instance, the temperature can be very high in case of heating induction furthermore, the integration of the temperature in the hysteresis model is imperative for a reliable estimate of losses related to this phenomenon.

Taking into account the variation of the five parameters model depending on the temperature during the integration of this model in a computer code by finite element field is a formidable task, especially in the study of magnetic electromagnetic device.

In this paper, we propose the introduction of temperature effect for the generation of hysteresis loops in the Jiles-Atherton model.

In this paper, we adopt a different approach of [1]. We introduced the two thermal behavior of the spontaneous magnetization M_s and coercive H_c in the parameter k of the Jiles-Atherton model.

2. The Jiles Atherton model

According to the Jiles–Atherton (JA) model [2], the total magnetization of a ferromagnetic material can be represented as the sum of contributions of irreversible, M_{irr}, and reversible, M_{rev}, magnetization components [2]:

(1) $$M = M_{rev} + M_{irr}$$

The reversible component is the combination of the reversible translation and rotation of the walls in ferromagnetic materials. But the irreversible component represents the irreversible displacement of the magnetic domains. The differential equation describing the dependence of magnetization on magnetic field can be constructed as

(2) $$M = M_{irr} + c\left(M_{an} - M_{irr}\right)$$

(3) $$M = M_{an} - k\delta \frac{dM_{irr}}{dH_e}$$

where M_{an} is the anhysteretic curve, which follows the Langevin function

(4) $$M_{an} = M_s\left(\coth\left(\frac{H_e}{a}\right) - \left(\frac{a}{H_e}\right)\right)$$

where $H_e = H + \alpha M$ is the effective field taking into account the domain interactions, α is the molecular field parameter, *k* parameter is linked to the coercitive field, *c* Reversibility coefficient and δ parameter is $\delta = +1$ when $\frac{dH}{dt} > 0$ and $\delta = -1$ when $\frac{dH}{dt} < 0$ [3].

The differential susceptibility according to the JA model can be expressed as follows [4].

(5) $$\frac{dM}{dH} = \frac{(1-c)\frac{dM_{irr}}{dH_e} + c\frac{dM_{an}}{dH_e}}{1 - \alpha c\frac{dM_{an}}{dH_e} - \alpha(1-c)\frac{dM_{irr}}{dH_e}}$$

3. Temperature Dependence of JA

Thermal effects can be incorporated into the model through the temperature dependence of hysteresis parameters in (5): spontaneous magnetization M_s, parameter α, reversibility factor *c and* parameter *k*.

a. Spontaneous magnetization M_s

The temperature dependence of spontaneous magnetization M_s can be expressed using Weiss theory of ferromagnetism [5].

(6) $$M_s(T) = M_s^{Ta}\left(1 - \exp\left(\frac{T - T_c}{\tau_{M_s}}\right)\right)$$

Where M_s^{Ta} is the value of spontaneous magnetization at room temperature, T_c is the Curie temperature, and τ_{M_s} is the constant defined on the experimental curve of spontaneous magnetization with temperature .

b. Parameter *a*

The parameter *a*, is treated as a constant in this model because its variation with temperature is negligible [6].

c. Parameter α

The parameter α, can be expressed in an isotropic material as [7]

(7) $$\alpha = \frac{3a}{M_s} - \frac{1}{\chi'_{an}}$$

Anhysteretic susceptibility χ'_{an} is generally very high, so the second term of the expression (7) is negligible compared to the first term of (7), and therefore the expression of the α parameter became

(8) $$\alpha = \frac{3a}{M_s}$$

(9) $$\alpha(T) = \frac{3a}{M_s^{Ta}} \frac{1}{(1 - \exp(\frac{T - T_c}{\tau_{M_s}}))}$$

(10) $$\alpha(T) = \alpha(T^{Ta}) \frac{1}{(1 - \exp(\frac{T - T_c}{\tau_{M_s}}))}$$

where α^{Ta} is the value of parameter α at room temperature [8].

c. Parameter *c*

The factor c, is expressed as [7]

(11) $$c = \frac{3a\chi'_{in}}{M_s}$$

Assuming constant initial susceptibility χ'_{in} and substituting the expression for M_s from (6), we get

(12) $$c(T) = \frac{3a}{M_s^{Ta}} \chi'_{in} \frac{1}{(1 - \exp(\frac{T - T_c}{\tau_{M_s}}))}$$

(13) $$c(T) = c^{Ta} \frac{1}{(1 - \exp(\frac{T - T_c}{\tau_{M_s}}))}$$

where c^{Ta} is the value of parameter c at room temperature.

e. Parameter k

The parameter k, can be expressed in an isotropic material as [7].

(14) $$k = \frac{M_{an}(H_c)}{(1-c)} \left[\alpha + \frac{1-c}{x_c - c\frac{dM_{an}(H_c)}{dH}} \right]$$

(15) $$M_{an}(H_c) = M_s \left(\coth\left(\frac{H_c}{a}\right) - \frac{a}{H_c} \right)$$

(16) $$\frac{dM_{an}(H_c)}{dH} = \left[\frac{M_s}{a} - \frac{M_{an}(H_c)}{a} \left(\frac{M_{an}(H_c)}{M_s} + \frac{2a}{H_c} \right) \right] (1 + \alpha\chi_c)$$

where H_c is the coercive field and χ_c is the susceptibility. The coercive field is a value strongly depends on the temperature [9]. Due to the exponential decay of coercive field in a ferromagnetic material [10], the coercive field should vary exponentially with temperature according to the equation

(17) $$H_c(T) = H_c^{Ta} \exp\left(-\frac{T}{\tau_{H_c} T_c} \right)$$

where H_c^{Ta} is the value of coercive field at room temperature and τ_{H_c} is the constant defined on the experimental curve of coercive field with temperature.

Assuming constant coercive susceptibility χ_c and substituting the expression for H_c from (17), we get

(18) $$M_{an}(T) = M_s(T) \left(\coth\left(\frac{H_c(T)}{a} \right) - \frac{a}{H_c(T)} \right)$$

(19) $$\frac{dM_{an}(T)}{dH} = \left[\frac{M_s(T)}{a} - \frac{M_{an}(T)}{a} \left(\frac{M_{an}(T)}{M_s(T)} + \frac{2a}{H_c(T)} \right) \right] (1 + \alpha(T)\chi_c)$$

The substitution of equations (6), (10), (13), (17), (18) and (19) in (14), gives the following expression

(20) $$k(T) = \frac{M_{an}(T)}{(1-c(T))} \left[\alpha(T) + \frac{1-c(T)}{x_c - c(T)\frac{dM_{an}(T)}{dH}} \right]$$

3.1. Parameter identification

The hysteresis parameters governing the magnetization processes *M_s, k, a, c* and α can be identified from the magnetic properties such as initial susceptibility χ'_{in}, anhysteretic susceptibility χ'_{an}, coercivity H_c, and remanence M_r. The identification procedures were calculated using an established procedure [11-12] which is sufficient for modelling purposes. The measured spontaneous magnetization M_s and coercive field as a function of temperature were used to estimate the τ_{M_s} and τ_{H_c}, by fitting the analytical model shown in (6) and (17). This procedure will to describe hysteretic behaviour at any temperature up to Curie point.

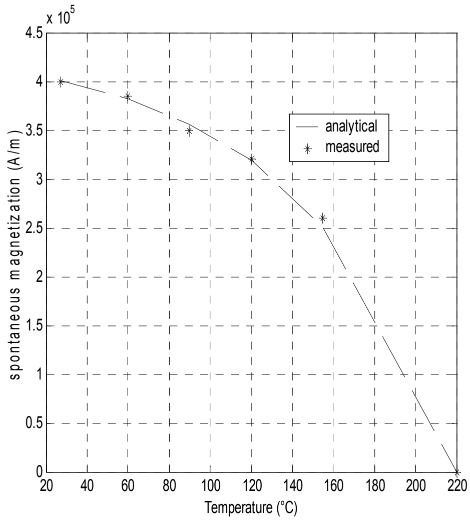

Fig.1. Variation of M_s with temperature

After identifying the necessary parameters to generate the hysteresis loop according to the temperature M_s^{Ta}, α^{Ta}, c^{Ta}, H_c^{Ta} and a, the evolution curve of M_s according to the temperature (fig 1) was used to identify the constant τ_{M_s}. The increase in temperature decreases the spontaneous magnetization, first slowly then more rapidly as one approaches the Curie point (Fig. 1). The parameter α and the parameter *c* increase monotonically with temperature, as shown in Fig. 3 and Fig.4 respectively.

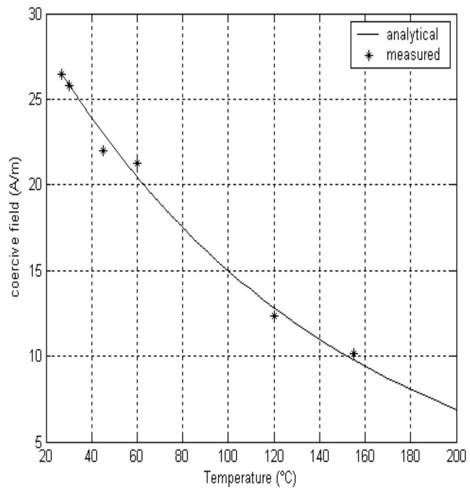

Fig. 2. Variation of Hc with temperature

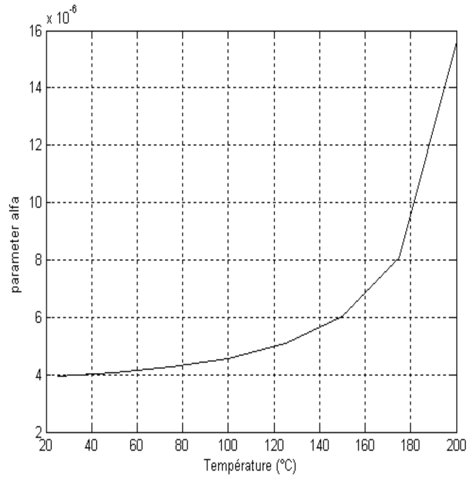

Fig .3. Calculated temperature dependence of parameter α

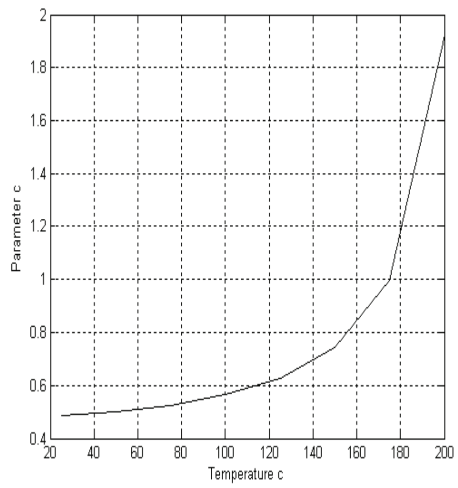

Fig 4. Calculated temperature dependence of parameter c

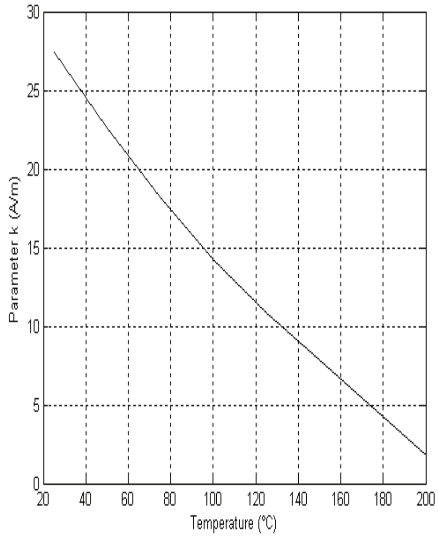

Fig. 5. Calculated temperature dependence of parameter *k*

The evolution curve of the coercive field H_c according to the temperature was used to identify τ_{H_c} constant. The coercive field decreases exponentially with temperature as shown in Fig 2. The tow laws of thermal behavior of M_s and H_c were introduced in the expression of the parameter *k*. The variation of this parameter with temperature is shown in Figure 5.

4. Comparison with experiments

Fig. 6 illustrates the experimental setup for measuring magnetic hysteresis loops at different temperatures using ring sample. The sample is a torus with primary and secondary windings. Excitation is applied using an arbitrary function generator which allows us to impose current or voltage on the primary winding. A computer remotely controls these devices. Using the Ampere and Faraday laws, the field *H* and the magnetic flux density *B* are calculated from the measurement of the current in the primary winding and the secondary winding voltage.

The sample under test was placed in the middle of an environment chamber, which could maintain a constant temperature over a wide range from 25 °C to 160 °C.

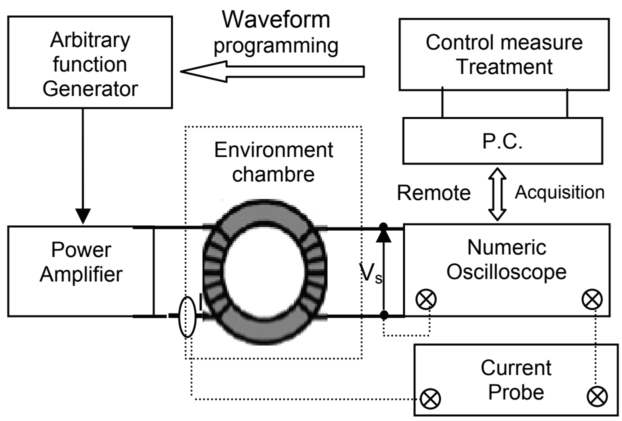

Fig. 6. Experimental setup for measuring magnetic hysteresis loops

The temperature dependent JA model was validated versus experimental data of ferrite 3F3 material with Curie point at 220°C. The hysteresis loops were measured using the experimental setup of Fig. 6 at various temperatures ranging from 27 °C to 155 °C and compared to those calculated numerically.

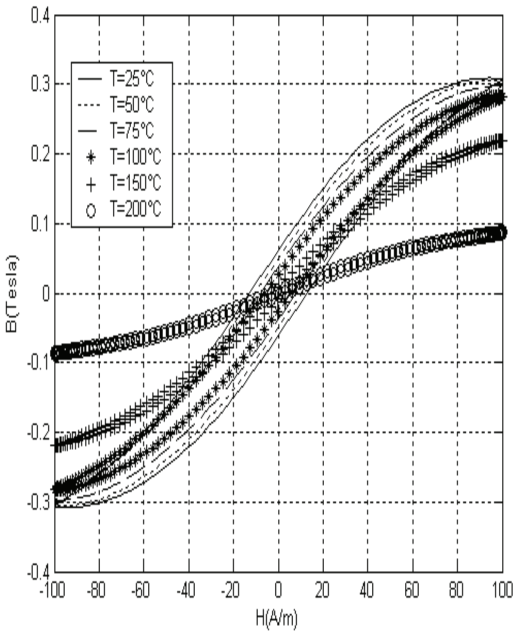

Fig7. Calculated temperature dependence of magnetic hysteresis loops in a 3F3 material

The measured and calculated hysteresis loops of 3F3 material at temperatures 27 ^{0}C , 60 ^{0}C, and 155 ^{0}C are compared in Fig. 8. The hysteresis loop gradually flattens as the temperature approaches the Curie point. After the Curie point, the material becomes paramagnetic and does not exhibit hysteresis. The calculated hysteresis loops start to deviate from the measured loops at higher temperatures. This behaviour could be due to the assumption that the χ_c susceptibility is independent of temperature in the used model.

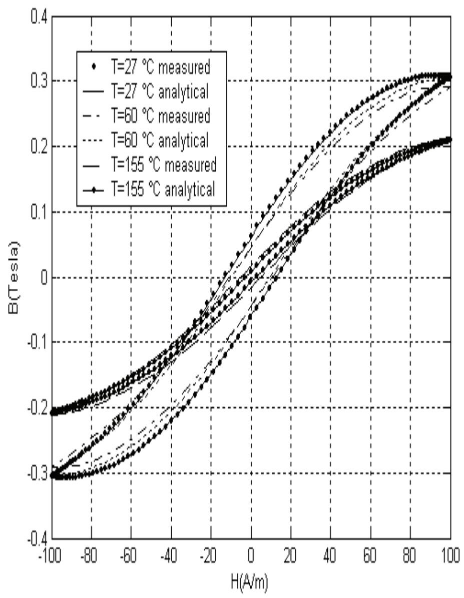

Fig.8. Variation of magnetic hysteresis loops with temperature in a 3F3 material with Curie point at Tc=220 °C.

Conclusion

In this work, a JA based model of hysteresis depending on temperature has been developed. Thermal effects have been introduced in the model of JA through two important values which enter into the construction of the magnetic hysteresis loop: spontaneous magnetization Ms and coercive Hc, the evolution curve of MS according to temperature was used to calculate the parameters α and c as a function of temperature, the evolution of M_s and H_c as a function of temperature was used to calculate the thermal behavior of the parameter *k*. The identification procedure for the proposed model is to calculate the model parameters at room temperature, and to determine the two constants, τ_{M_s} and τ_{H_c}, from the evolution of M_s and H_c as a function of temperature. The model can be further improved if an analytical model of temperature dependence of the coercive susceptibility χ_c is implemented.

The temperature-dependent JA model was validated versus measurements made on ferrite (3F3). The comparison showed that the temperature-dependent Jiles Atherton model was in good agreement with the measurements.

REFERENCES

[1] A. Raghunathan, Y. Melikhov, J. E. Snyder, and D. C. Jiles, Theoretical model of dependence of hysteresis based mean field theory, IEEE Transactions on Magnetics, vol. 46, no. 6, pp, 1507- 1509, 2010.
[2] D.C. Jiles, D.L. Atherton, Theory of ferromagnetic hysteresis, Journal of Magnetism and magnetic materials Vol. 61, 1986. pp 48-60.
[3] D. C. Jiles, Introduction to Magnetism and Magnetic Materials, London, U.K.: Chapman & Hall, 1991.
[4] G.S. Park, S.Y. Hahn, K.S. Lee, H.K. Jung. IEEE Transactions on Magnetic. 29 (2) (1993) 1542.
[5] H. Bleuvin, Analyse par la méthode des éléments finis des phénomènes magnéto-thermiques – application aux systèmes de chauffage par induction, Phd Thesis, Polytechnic institute of Grenoble, 1984.
[6] P. R. Wilson, J. N. Ross, and A. D. Brown, “Simulation of magnetic component models in electric circuits including dynamic thermal effects,” *IEEE Trans. Power Electron.*, vol. 17, no. 1, pp. 55–65, Jan. 2002.
[7] D.C. Jiles, J.B. Thoelke et M.K. Devine, Numerical determination of hysteresis parameters for the modeling of magnetic properties using the theory of ferromagnetic hysteresis, *IEEE Transactions on Magnetics*, Vol. 28, pp. 27-35, 1992.
[8] A. Raghunathan, Y. Melikhov, J. E. Snyder, and D. C. Jiles, Modeling the Temperature dependence of hysteresis based on Jiles-Atherton theory, *IEEE Transactions on Magnetics*, Vol. 45, N0. 10, pp. 3954- 3957, 2009.
[9] O. Benda, V. Ac, New Approach to Experimental Investigation of Coercivity Temperature Dependence, IEEE Transactions on Magnetics., vol. 3, n0. 3, pp, 518-521, 1967.
[10] J. Hauschild, H. Fritzsche, S. Bonn, and Y. Liu, “Determination of the temperature dependence of the coercivity in Fe/Cr (110) multilayers,” *Appl. Phys. A: Mater. Sci. Process.*, vol. 74, pp. S1541–S1543, 2002.
[11] A. Benabou, S. Cl!enet, F. Piriou, Comparison of Preisach and Jiles–Atherton models to take into account hysteresis phenomenon for finite element analysis, Journal of Magnetism and Magnetic Materials Vol. 261, 2003. pp 139-160.
[12] A. Benabou, Identification et optimisation des paramètres du modèle de Jiles-Atherton pour la modélisation de l’hystérésis magnétique , JGGE’01 Nancy (France), 13-14 Novembre, pp. 229-234, 2001.

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