Temperature dependent extension of a hysteresis model

Fabien Sixdenier[1], Oualid Messal[2], Alaa Hilal[1], Christian Martin[1], Marie-Ange Raulet[1]

[1]Université de Lyon, Université Lyon 1, CNRS UMR5005 AMPERE, 41, Blvd Latarjet, Villeurbanne, F69622, France
[2] Grenoble INP - UJF Grenoble 1 - CNRS UMR 5269 (G2Elab), Saint Martin d'Hères Cedex, 38402, France

Some soft magnetic materials (like ferrites but not only) are strongly dependent of the temperature. In order to predict their behaviour in electrical devices, engineers need hysteresis models able to take into account the temperature. This paper is an attempt to take into account the temperature in an existing model of hysteresis through its parameters. Variations of some parameters are issued from Weiss's works and others have to be fitted numerically. Simulation results are compared to measurements and discussed.

***Index Terms*—Temperature dependance, magnetic losses, thermal stresses,. . .**

I. Introduction

In order to reduce the volume/mass of soft magnetic materials in electrical devices, there are two main solutions: increase the "working" induction level $\widehat{B}$ or increase the frequency f. The both solutions lead to increase the magnetic losses p_{fe} of the device and consequently increase the temperature due to self heating. Moreover, soft magnetic materials are strongly dependent on the temperature and this behaviour is highly non-linear. Thus, designers need models able to predict the magnetic behaviour in a "large" temperature range, from 25 °C to the Curie temperature T_c. In [1], the authors used the Jiles-Atherthon (JA) model and analytical equations for each parameter. They retrieved qualitatively the measured behaviour with monotonic evolution of each parameter but the errors were quite high. In [2], the authors used an optimization method to identify the parameters. The results were very good regarding the accuracy, but the evolution of some parameters with temperature was erratic. By using both analytical laws [3] and optimization methods in [4], a good compromise between the error levels and the monotony of the parameters has been achieved. Nevertheless, for complex induction $b(t)$ waveforms, JA model fails to predict excitation field $h(t)$ with accuracy due to several intrinsic drawbacks of the models well detailed in [5]. Engineers need, then, a reliable model of hysteresis able to take into account both complex inductions waveforms and the temperature. We propose here to adapt an existing model of hysteresis [6] recently improved in [7], in order to take into account the temperature, through its parameters especially the magnetic polarization. It differs from [8] where the authors consider, in other things, the evolution of the coercive field instead.

II. Modelling approach

A. Vectorial Incremental Nonconservative Consistent Hysteresis model

The Vectorial Incremental Nonconservative Consistent Hysteresis (VINCH) model [6], is used to model the hysteresis phenomenon. Its advantages are: it is a readily vectorial model and it relies on a consistent thermodynamic formulation. Unlike the JA model, its number of parameters is not limited. We will here present just a reminder of the principle, the equations and the parameters of the model. The model consists on minimizing, at each time step (one value of h), the functional Ω (1).

$$\Omega = \sum_{k=1}^{N} \Omega^k = \sum_{k=1}^{N} \left(u(J^k) - h \cdot J^k + \chi^k |J^k - J_p^k| \right) \quad (1)$$

In (1), N is the number of functional equations to minimize, h is the applied field, J_p^k is the magnetic polarization of the functional Ω^k at the the previous step, χ^k is a model parameter and J^k is the value of J that minimizes the functional Ω^k. Finally $u(k)$ is defined by (2)

$$u\left(J^k\right) = \int_o^{J^k} h_r^k(x) dx \quad (2)$$

$$h_r^k(J) = \alpha \cdot tanh^{-1}(J^k/J_s^k) \quad (3)$$

In (3), J_s^k is the saturation polarisation of the k functional. For N functionals, one has to identify $2N+1$ parameters (J_s^k, χ^k, α). The initial saturation slope α is supposed identical for all functionals. The pairs (J_s^k, χ^k) can be identified for increasing values of χ^k thanks to the first magnetization curve [6] or thanks to the curve of the coercive field $h_c(h_{peak})$ [9]. For a given time step, one has to find all values of J^k that minimize Ω. b can be retrieved by (4).

$$b = \mu_0 h + \sum_{k=1}^{N} J^k \quad (4)$$

B. Temperature extension

As the saturation polarization J_s of a ferromagnetic material can be assumed to be function of the temperature T following the law (5) [3], with J_{s0} the polarization at $T = 0$ K and T_c the Curie temperature. It is assumed in this approach that each J_s^k will follow the same law.

$$\frac{J_s}{J_{s0}} = \tanh\left(\frac{J_s/J_{s0}}{T/T_c}\right) \quad (5)$$

The χ^k are keeped constant, it lets only α to identify numerically (fitting). α is normally inversely proportional to the slope of the $B(H)$ loop.

III. Results

We chose to test this approach on an alloy, named Phyterm260 commercialized by the APERAM company[10]. This alloy is normally dedicated to induction cookwares. It is a $Ni_{50}Fe_{bal}Cr_9$ alloy with a Curie temperature around 260 °C. The table I shows the values of the parameters χ_k and J_s^k for the temperature of 19 °C. For other temperatures, χ_k are kept constant and J_s^k follow the law given by (5), with $J_{s0} = 0.83$ T and $T_c = 260$ °C. The table II shows the values of the α parameter after fitting. Finally, Fig. 1 and Fig. 2 show the measured and simulated hysteresis loops at different temperatures respectively .

TABLE I
Parameters values at T =19 °C

k	1	2	3	4	5	6	7
χ^k (A/m)	0	5	10	15	20	25	50
J_s^k (mT)	0.2	4.1	2	149.4	124.8	404.7	1.1

TABLE II
α values

T (°C)	19	80	120	180	220	240
α (A/m)	65	68	60	86	84	99

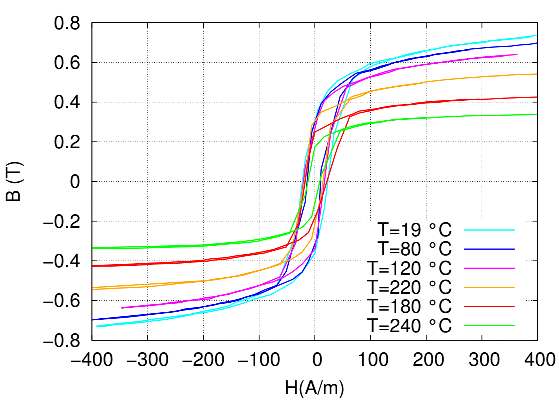

Fig. 1. Measured hysteresis loops at different temperatures

The evolution of the simulated hysteresis loops with the increasing temperature is globally respected. Some problems still remain, such as α is overestimated (it flattens the loops too much) and the saturation is quite an horizontal line (this is not the case for the measured loops). These both problems are mainly due to (3) where the $tanh^{-1}$ function is not the best one for the case of this material. Some more realistic functions (like Langevin function) but less convenient (not explicit) functions can be chosen [9].

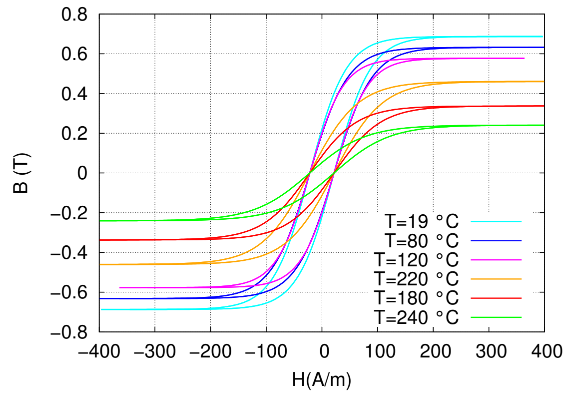

Fig. 2. Simulated hysteresis loops at different temperatures

IV. Conclusion

In this paper, a first attempt to take into account the temperature in an existing hysteresis model has been made. The concept is to adapt some of the parameters values with the temperature (J_s^k and α). The J_s^k values follow the same variations of the macroscopic saturation polarization J_s defined by Weiss (5) and α is fitted numerically. First results are promising but some efforts have to be made in order to increase the accuracy. In the extended paper, more realistic functions for (3) will be tested in this last aim. Some other materials (like ferrites) will also be tested with the same approach to test the robustness of the approach.

References

[1] Y. Raghunathan, J. Melikhov, E. Snyder, and D. Jiles, “Modeling the temperature dependance of hysteresis based on jiles-atherton theory,” *IEEE Transactions on Magnetics*, vol. 45, no. 10, pp. 3954–3957, 2009.

[2] O. Messal, F. Sixdenier, L. Morel, and N. Burais, “Temperature dependent extension of the jiles-atherton model: Study of the variation of microstructural hysteresis parameters,” *IEEE Transactions on Magnetics*, vol. 48, no. 10, pp. 2567–2572, 2012.

[3] P. Weiss, “La constante du champ moléculaire. equation d’état et calorimétrie,” *Journal de Physique*, vol. 1, no. 5, pp. 163–175, 1930.

[4] O. Messal, F. Sixdenier, L. Morel, and N. Burais, “Thermal behavior of iron-nickel-chromium alloys and correlation with magnetic and physical properties - part a: Static effects modeling,” in *Proceedings of the 19th Conference on the Computation of Electromagnetic Fields*. Budapest : Hungary: Compumag 2013, July 2013.

[5] S. Zirka, Y. Moroz, R. Harrison, and K. Chwastek, “On physical aspects of the jiles-atherton hysteresis models,” *JOURNAL OF APPLIED PHYSICS*, vol. 112, no. 4, pp. 043 916 – 043 916–7, 2012.

[6] V. François-Lavet, F. Henrotte, L. Stainier, L. Noels, and C. Geuzaine, “Vectorial incremental nonconservative consistent hysteresis model,” in *Proceedings of the 5th International Conference on Advanded COmputational Methods in Engineering (ACOMEN2011)*. Liège, Belgium: ACOMEN2011, November 2011.

[7] A. Bergqvist, D. Lin, and P. Zhou, “Temperature-dependent vector hysteresis model for permanent magnets,” *IEEE Transactions on Magnetics*, vol. 50, no. 2, p. 7008404, 2014.

[8] D. Lin, P. Zhou, and A. Bergqvist, “Improved vector play model and parameter identification for magnetic hysteresis materials,” *IEEE Transactions on Magnetics*, vol. 50, no. 2, p. 7008704, 2014.

[9] F. Henrotte, A. Nicolet, and K. Hameyer, “An energy-based vector hysteresis model for ferromagnetic materials,” *COMPEL*, vol. 25, no. 1, pp. 71–80, 2006.

[10] APERAM. [Online]. Available: http://www.aperam.com/en/alloys-amilly/downloads/datasheet/