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Analysis of GRUCAD Model Behavior for Anhysteretic Curve Given by the Brillouin Function

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The paper focuses on an extension of the GRUCAD hysteresis model. The extension relies on the replacement of the Langevin function with a more general Brillouin function in an equation describing the anhysteretic curve. The proposed approach allows one to obtain better fitting capabilities for anisotropic soft magnetic materials, as demonstrated by the example of hysteresis curves of grain-oriented electrical steel.

topics: electrical steel, modeling, hysteresis curve, anhysteretic curve

1. Introduction

Taking into account that any magnetic hysteresis model is merely an approximation of real-life phenomena, it can be stated that an important stage in hysteresis modeling is the analysis of the qualitative behavior of models with different improvements.

Improvements can be understood as modifications of model equations, extensions aimed at correcting model behavior, or considerations of physical phenomena, such as the effect of excitation frequency, mechanical stress anisotropy, or temperature, which previously were not taken into account.

An exemplary modification may rely on the use of different elementary functions appearing in model equations. It is expected that model performance would be improved for different scenarios, and moreover, new knowledge on underlying physical principles would be gained. In the present paper, we consider an extension to the GRUCAD model [1], which uses a more general description of the anhysteretic curve in comparison to the original approach. The GRUCAD model is a recent low-dimensional description consistent with the laws of irreversible thermodynamics.

2. Model description

The description advanced by Jiles and Atherton [2] has attracted a lot of attention in the scientific community in the last thirty years. This formalism is still very attractive to scientists and engineers alike. In the present paper, we focus on the GRUCAD model, which is a modification of the Jiles–Atherton (JA) approach proposed by the Brazilian GRUCAD [1, 3]. The most important advantage of GRUCAD model is that it addresses a number of problems encountered in the original description, as pointed out in [4, 5]. The crucial difference between the original JA formalism and the GRUCAD model is that the latter description uses offsetting (shifting) from the anhysteretic curve along the H axis, not along the M axis. This feature allows one to obtain quasi-static minor hysteresis loops without fragments with negative differential susceptibility, and moreover, it is correct from the perspective of energy balance relationships. As a reminder, the anhysteretic curve describes the state of global equilibrium in the thermodynamic sense.

The GRUCAD description has yet another important feature, namely it is formulated as a B-input model — this feature facilitates the interpretation of results. Magnetic measurements carried out in accordance with international standards are carried out for a controlled polarization rate (in practice, for soft magnetic materials, the difference between polarization and flux density may be neglected). Thus, the model reflects real-life measurement conditions.

Previously, the behavior of the GRUCAD model was analyzed in some papers co-authored by the authors of the present contribution, mentioning, e.g., its application in describing hysteresis curves in a permalloy core [6], soft magnetic composites [7, 8], magnetocaloric LaFeCoSi alloys [9]. An extension aimed at consideration of the effect of excitation frequency was attempted for a nanocrystalline sample in [10], whereas paper [11] focused on model behavior in the case of DC-biased magnetization.

The set of equations used so far was

$$H_{\text{an}} = \frac{B}{\mu_0} - M_s\left[\coth(\lambda) - \frac{1}{\lambda}\right], \tag{1}$$

$$\lambda = \frac{H_{\text{an}}\,(1-\alpha) + B(\frac{\alpha}{\mu_0})}{a}, \tag{2}$$

$$\frac{\mathrm{d}H_{\text{h}}}{\mathrm{d}B} = \frac{H_{\text{HS}}\left[\coth(\lambda_H) - 1/\lambda_H\right] - H_{\text{h}}}{\gamma\delta}, \tag{3}$$

$$\lambda_H = \frac{H_{\text{h}} + \delta H_{\text{HS}}}{a}, \tag{4}$$

$$H = H_{\text{an}} + H_{\text{h}}, \tag{5}$$

where α, a, γ, H_{HS}, and M_s were model parameters; $\delta = \pm 1$ was used to distinguish the ascending and descending loop branches; λ and λ_H were auxiliary variables; $H_{\text{an}} = H_{\text{an}}(B)$ was the anhysteretic field strength, and $H_{\text{h}} = H_{\text{h}}(B)$ denoted the irreversible field strength, related to hysteresis; μ_0 was permeability of free space; and B was magnetic flux density, which was the input variable in the model.

3. Comparison of different anhysteretic equations

In the preceding section, expressions (1) and (2) were used as a complete description of the anhysteretic curve. It can be easily noticed that (1) availed of the Langevin function.

The aim of the present paper is to introduce in that place a more general function, namely the Brillouin function

$$B_J\,(\lambda) = \frac{2J{+}1}{2J}\coth\left(\frac{2J{+}1}{2J}\lambda\right) - \frac{1}{2J}\coth\left(\frac{1}{2J}\lambda\right), \tag{6}$$

in which an additional parameter J appears. In solid-state physics, it is interpreted as an angular momentum quantum number. It takes either positive integer or half-integer values. Two limiting values are 0.5 (then the Brillouin function reduces to hyperbolic tangent) and ∞ (in practical computation $J \to 25$, then the Brillouin function approaches the Langevin function).

Exemplary shapes of curves reproduced with the Brillouin function in reduced units for different values of J parameter are depicted in Fig. 1. Additionally, in this figure, the dependence $y = \tanh(x/3)$ is shown. This dependence may be used instead of the Langevin function for smaller values of its argument, and the advantage of this function is that it can be inverted analytically.

The extension considered in this paper bears some resemblance to the approaches described in [12, 13]. The aforementioned papers considered that the proper choice of angular momentum quantum number J in the formula for the anhysteretic curve in the modified JA description might shed some light on the anisotropy class of the analyzed soft magnetic material. The present paper applied the same concept to another model, which, in our opinion, is a much better choice for people dealing with hysteresis modeling.

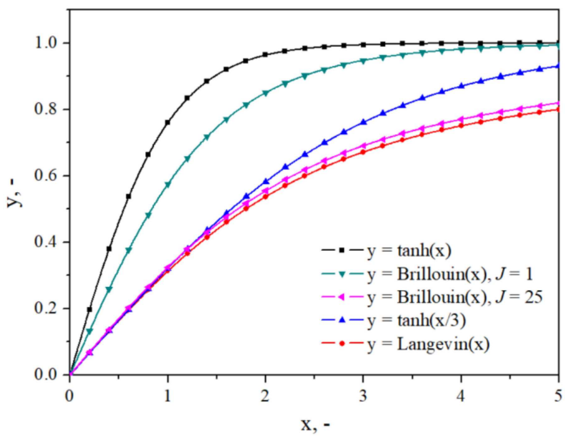

Fig. 1. The functions $L\,(x)$, $\tanh(x/3)$, and $B_J(x)$ for $J = 1.0$ and $J = 25$.

Replacing the Langevin function with the Brillouin function in (1) is the only modification applied to model equations in this paper. The concept is to vary the value of parameter J and to find such a set of model parameters that yields the best match to the measured hysteresis curve.

4. Modeling

In the present paper, we focus on modeling properties of samples made of two kinds of electrical steel, differing in morphology and magnetic properties. The rationale for our choice is that electrical steels are the most dominant group of soft magnetic materials worldwide (around 80% are non-oriented (NO) electrical steels, used as core materials for rotating machines, and around 16% are grain-oriented (GO) steels, whose application target are magnetic circuits of power and distributions transformers).

We consider two representative samples from each group, namely the grade M330-35A (NO steel, 0.35 mm thick) and the grade ET120-27 (GO steel, 0.27 mm thick).

Figures 2 and 3 depict modeling results for the non-oriented steel. Two extreme cases of the J value are considered for brevity. From the inspection of these figures, it is noticeable that the choice of $J = 25$ in the Brillouin function allows us to reproduce the shape of hysteresis slightly more accurately, in particular in the so-called knee region.

Figures 4 and 5 refer to grain-oriented electrical steel ET120-27, which exhibits a substantial anisotropy. The measurements were carried out along the rolling direction.

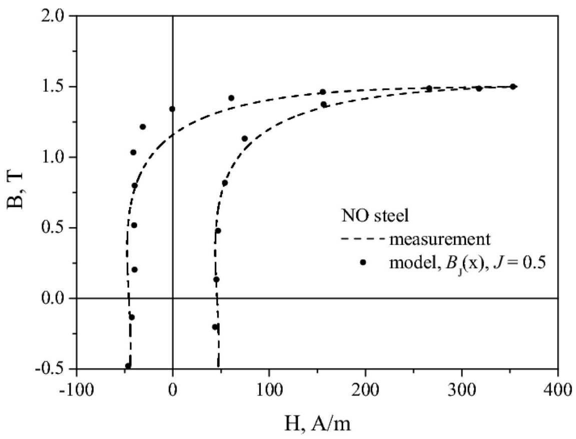

Fig. 2. The measured and the modeled hysteresis loop for the NO sample. The anhysteretic curve is given as $B_J(x)$, $J = 0.5$.

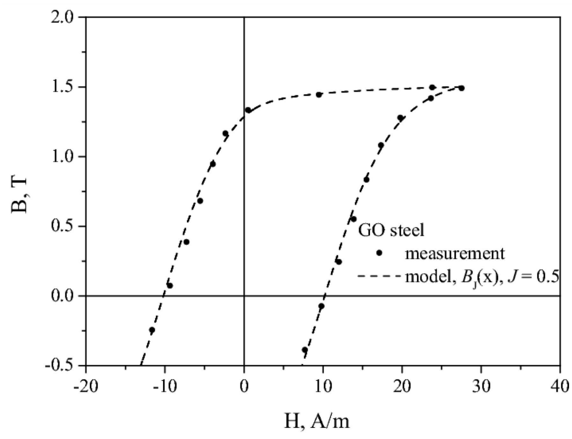

Fig. 4. The measured and the modeled hysteresis loop for the GO sample. The anhysteretic curve is given as $B_J(x)$, $J = 0.5$.

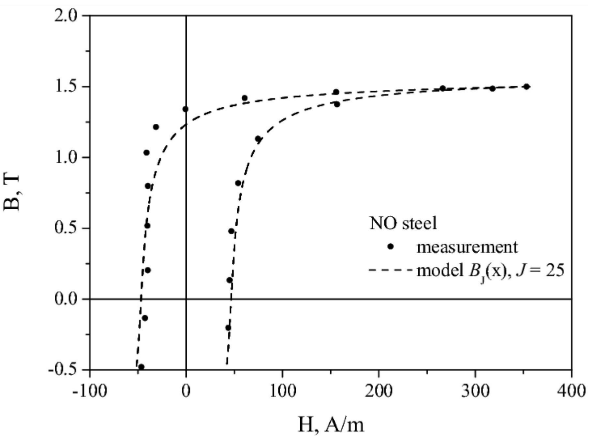

Fig. 3. The measured and the modeled hysteresis loop for the NO sample. The anhysteretic curve is given as $B_J(x)$, $J = 25$.

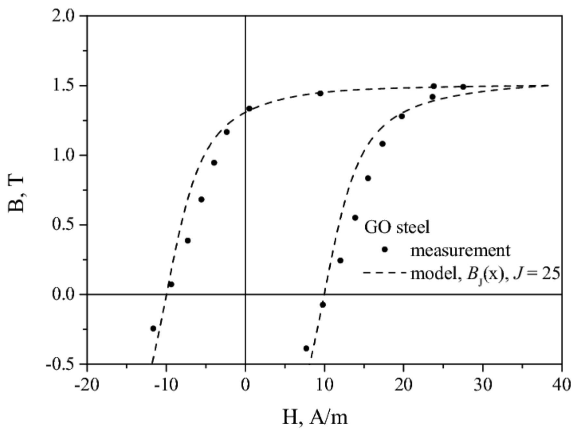

Fig. 5. The measured and the modeled hysteresis loop for the GO sample. The anhysteretic curve is given as $B_J(x)$, $J = 25$.

TABLE I

Values and percentage errors in chosen characteristic points for the non-oriented steel.

	H_c [A/m]	B_r [T]	$\|\Delta H_c\|$	$\|\Delta B_r\|$	$\|\Delta E\|$
Meas.	43.9	1.36			
$B(x)$ $J = 0.5$	45.8	1.15	4.3%	15.4%	7.5%
$B(x)$ $J = 5$	45.8	1.21	4.3%	10.9%	7.3%
$B(x)$ $J = 10$	43.1	1.11	1.9%	18.7%	27%
$B(x)$ $J = 15$	44.9	1.23	2.2%	9.7%	11%
$B(x)$ $J = 25$	44.3	1.23	2.8%	9.3%	10%
$L(x)$	45.3	1.25	3.1%	8.1%	8.4%

TABLE II

Values and percentage errors in chosen characteristic points for the grain-oriented steel.

	H_c [A/m]	B_r [T]	$\|\Delta H_c\|$	$\|\Delta B_r\|$	$\|\Delta E\|$
Meas.	10.00	1.30			
$B(x)$ $J = 0.5$	10.25	1.29	2.5%	1%	0.6%
$B(x)$ $J = 5$	9.85	1.37	1.5%	5%	2.6%
$B(x)$ $J = 10$	10.14	1.31	1.4%	1%	5.3%
$B(x)$ $J = 15$	10.02	1.30	0.2%	0%	3.7%
$B(x)$ $J = 25$	9.96	1.31	0.4%	1%	0.2%
$L(x)$	10.50	1.32	5.0%	2%	1.1%

Tables I and II contain information on measured and modeled values of coercive field strength and remanence induction for several selected values of J parameter. The last column (ΔE) refers to the relative difference between measured and modeled loop areas. Recalling that the hysteresis loop area is directly related to re-magnetization loss (the latter quantity may be computed from the loop area), the value of this parameter is an indirect measure of the modeling accuracy.

From the analysis of errors in the tables, it follows that, particularly for the GO steel, the modeling errors were dependent on the choice of J value. Despite the fact that the values in the table might suggest that the choice $J = 25$ is superior to $J = 0.5$, from a visual comparison of the modeled curves in Figs. 4 and 5, it follows that, in fact, the modeled curve for $J = 0.5$ describes the experimental data more accurately. Therefore, the choice $J = 0.5$ (the case of strong anisotropy) is preferred. Our model extension has proven to be useful.

5. Conclusions

In the paper, an extension to the GRUCAD hysteresis model was proposed. The essential concept was to modify one of the model equations. The Brillouin function was introduced in place of the Langevin function. This approach allowed us to make the description more flexible, enabling the consideration of different anisotropy classes of soft magnetic materials, which can be taken into account in the analysis by a proper choice of J parameter. The Langevin function is a limiting case of the Brillouin function obtained for $J \to \infty$.

The usefulness of the proposed model extension was verified using data for a strongly anisotropic material, namely grain-oriented electrical steel.

Future work will focus on additional verification of the proposed descriptions for other soft magnetic materials.

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