1. Krzysztof CHWASTEK[1], 2. Branko KOPRIVICA[2], 3. Marko ROSIĆ[2],
4. Roman GOZDUR[3], 5. Piotr GĘBARA[1]

Czestochowa University of Technology, Poland (1), University of Kragujevac, Serbia (2), Lodz University of Technology, Poland (3)
ORCID: 1. 0000-0002-2294-9976; 2. 0000-0001-5014-6866; 3. 0000-0001-7846-7004; 4. 0000-0003-1003-7635; 5. 0000-0003-4578-6556

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Modelling hysteresis loops of non-oriented electrical steel

***Abstract**. Non-oriented electrical steels constitute the most important segment of the market of soft magnetic materials. In the paper the usefulness of the model based on hyperbolic tangent nonlinear transformation for the description of quasi-static hysteresis loops for this type of material is verified.*

***Streszczenie.** Blachy elektrotechniczne o ziarnach niezorientowanych stanowią najważniejszy segment rynku materiałów magnetycznie miękkich. W pracy zweryfikowano użyteczność modelu opartego na nieliniowej transformacji tangens hiperboliczny do opisu quasi-statycznych pętli histerezy dla tego typu materiału .(**Modelowanie pętli histerezy stali elektrotechnicznej o ziarnach niezorientowanych**).*

Keywords Non-oriented steel; hysteresis loops; anisotropy; modelling
Słowa kluczowe Blacha o ziarnach niezorientowanych; pętle histerezy; anizotropia; modelowanie

Introduction

Non-oriented electrical steels (NOES) are the most important group of soft magnetic materials (SMMs). Their share is estimated at 80% [1], whereas their market size was valued at 12.57 billion USD in 2020 [2]. NOES are used in rotating electrical machines, ranging from generators for wind turbines to motors for the transportation sectors and small motors for household appliances [3]. The designers of magnetic circuits in these devices need more and more sophisticated CAD tools in order to optimize their designs and to develop eco-friendly and efficient solutions.

The present paper is a follow-up of previous research [4]. The aforementioned paper considered the possibility to describe hysteresis loops of grain-oriented electrical steels used mostly in magnetic circuits of power and distribution transformers with the T(x) hysteresis model [5].

Foundations of the T(x) model

The T(x) model is a versatile tool, based on hyperbolic tangent transformation. Its developer used an abstract notation with dimensionless units [5], cf. for example the expression for symmetric loops, which is written as

$$y = tanh\left(x \mp a_0\right) \pm b \tag{1}$$

where: x and y are, respectively, model input and output from the causal perspective, a_0 is coercive field strength in dimensionless units, whereas b is introduced in order to match loop branches at tips with coordinates $\pm x_m$

$$b = 0.5\left[tanh\left(x_m + a_0\right) - tanh\left(x_m - a_0\right)\right]. \tag{2}$$

For the major hysteresis loop $b \cong 0$.

A physical interpretation of variables appearing in the description was introduced in [6]. The variable x was interpreted as reduced "effective field", whereas y as magnetization. The "effective field" is a useful engineering framework, which makes it possible to take into account the effects of various physical phenomena affecting the shape of hysteresis loop like magnetostriction, temperature gradient, viscosity, cf. [7] for details.

The starting point for modelling is the proper description of the so-called anhysteretic curve. According to Takács, this curve corresponds to the global equilibrium in the thermodynamic sense and it is equally important as its purely irreversible counterpart i.e. the hysteresis loop [8].

Within the T(x) modelling framework the relationship for the anhysteretic curve is uniquely defined, this feature should be stressed out, since in some other approaches like the Jiles-Atherton (JA) model [9] and its extensions, e.g. [10,11], the model developers adapted for this purpose some arbitrarily chosen phenomenological formulas, borrowed from solid state physics theories.

The only assumption made within the T(x) modelling framework is that the curvatures of loop branches may be satisfactorily described with hyperbolic tangent function. The explicit mathematical expression for the anhysteretic curve is equivalent to relationship (2) if one replaces $b \to y_{anh}$ and $x_m \to x$. Moreover the subtraction of two $\tanh$ terms is replaced with their summation. Thus the geometric interpretation of the anhysteretic may be found immediately: this curve is the locus of loop tips. It is remarkable that there exists a deep connection between the anhysteretic curve representing purely reversible magnetization process and its corresponding counterpart i.e. the hysteresis loop.

The relationship $x = x(y_{anh})$ for the inverse anhysteretic curve, in which y_{anh} is swept between the limiting values $\pm y_m$ may be written as

$$x = atanh\left\{\frac{\sqrt{\left(1 - T^2\left(a_0\right)\right)^2 + 4T^2\left(a_0\right)y_{anh}^2} - \left(1 - T^2\left(a_0\right)\right)}{2T^2\left(a_0\right)y_{anh}}\right\} \tag{3}$$

where T is an abbreviation for the $tanh$ function. For $y_{anh} = 0$ there is no singularity, since $x \equiv 0$ [4] (this point is cumbersome for the JA model users).

As the anhysteretic curve is determined, in the next step the value for the normalization constant b is computed from (2), subsequently the shapes of loop branches are calculated from transformed relationship (1), solved for x.

It can be remarked that the afore-described procedure corresponds to the conditions in which soft magnetic materials are characterized [12].

The basic computational flowchart has to be supplemented with additional relationships, which make it possible to transform the dimensionless variables into physical ones and vice versa. Explicit formulas are provided in [4,6]. In the present paper we use the straightforward substitutions $x = (H + \alpha M)/a$ and $y = M/M_s$ where dimensionless α is the so-called Weiss' mean field parameter, whose value may be assumed as $\alpha \approx H_c/M_s$ in a wide range of excitation levels, whereas a, A/m, is a normalization constant. As a rule of thumb its value is so chosen, that saturation occurs for $x = 4...5$. In our computations we follow the strategy described as model 1 in Ref. [4].

Measurements and modelling

Measurements of magnetic properties for an exemplary NO steel (grade M530-50, dimensions 500 x 500 mm) were carried out the Single Sheet Tester and a computer-aided system MAG-RJJ-2.0 [13] for two principal directions. Despite the steel is referred to as non-oriented, it exhibits substantial anisotropy of its magnetic properties [14-16]. Figures 1 and 2 depict the families of hysteresis loops measured at quasi-static magnetization conditions (excitation frequency $f = 5$ Hz).

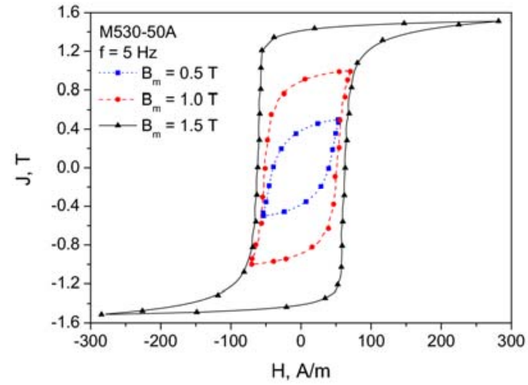

Fig.1. Measured quasi-static hysteresis loops for a typical non-oriented electrical steel sheet, 0.5 mm thick, rolling direction

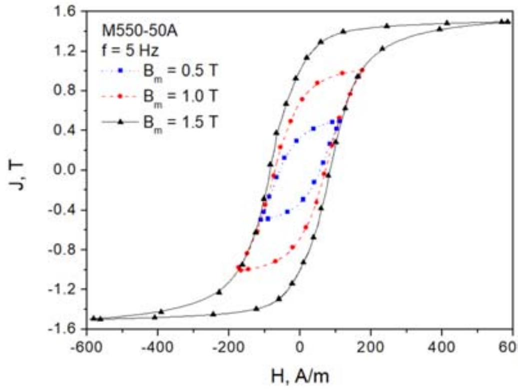

Fig.2. Measured quasi-static hysteresis loops for a typical non-oriented electrical steel sheet, 0.5 mm thick, transverse direction

Estimation of model parameters was carried with the robust DIRECT code [17]. Despite the estimation procedure seems trivial at first glance, it has to be stated that due to implicit existence of magnetization on both sides of the relationship equivalent to (1) (magnetization appears as part of the effective field) it was necessary to resort to numerical methods (i.e. Newton-Raphson algorithm) during computations.

The estimated set of model parameters were:

$\alpha = 4{,}1\cdot 10^{-5}$, $a = 68$ A/m, $H_{c0} = 68$ A/m,

$M_s = 1{,}29\cdot 10^{6}$ A/m for the rolling direction and

$\alpha = 4{,}1\cdot 10^{-5}$, $a = 188{,}3$ A/m, $H_{c0} = 91$ A/m,

$M_s = 1{,}29\cdot 10^{6}$ A/m for the transverse direction, respectively. Modeling results for the loops approaching saturation are depicted in Fig. 3 and Fig. 4. It can be stated that the modelled loops reproduced the measurement data in a satisfactory way. Figure 3 additionally depicts the modelled hysteresis loop in the $M - H_{eff}$ coordinate system (dotted lines).

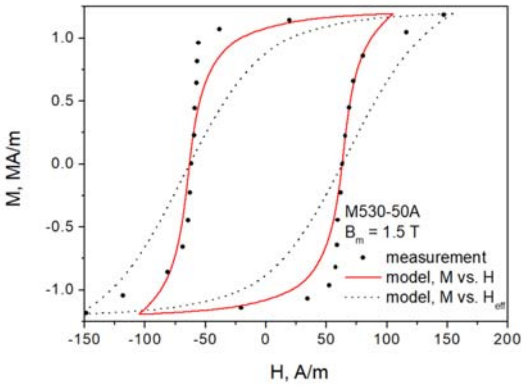

Fig.3. A comparison of measured (dots) and modelled major hysteresis loops for the rolling direction, $f = 5$ Hz

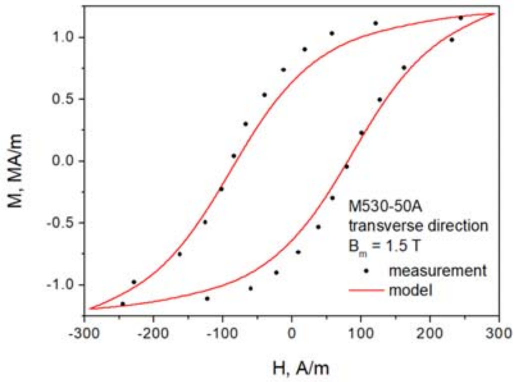

Fig.4. A comparison of measured (dots) and modelled major hysteresis loops for the transverse direction, $f = 5$ Hz

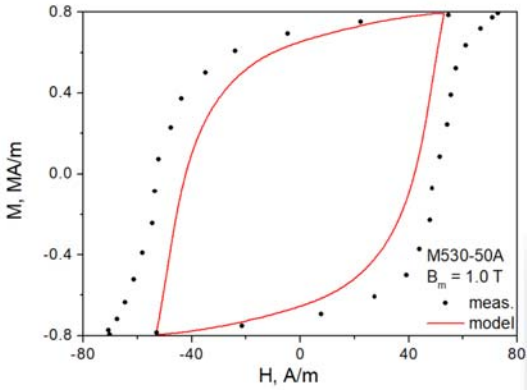

Fig.5. A comparison of measured (dots) and modelled minor hysteresis loops for the rolling direction, $f = 5$ Hz

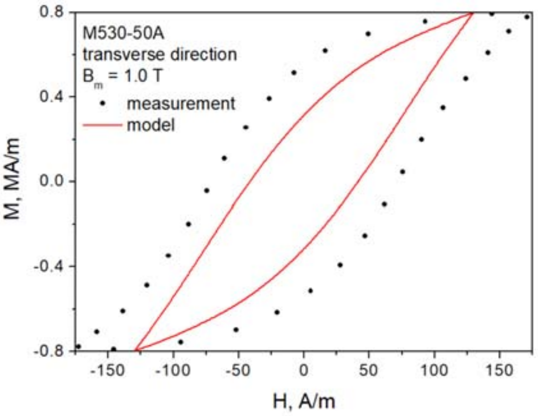

Fig.6. A comparison of measured (dots) and modelled minor hysteresis loops for the transverse direction, $f = 5$ Hz

Figures 5 and 6 depicts a comparison of measured and modelled minor loops for both directions, $B_{\mathrm{m}} = 1.0$ T, $f = 5$ Hz. From the inspection of figures it is evident that modelled minor loops are only in qualitative agreement with experiment. The discrepancies are particularly visible for the transverse direction. Most probably the T(x) model performs better for narrow loops like those exhibited by GO steel. Another possibility is that for the considered steel grade the measured hysteresis loops included a significant contribution from eddy current loss already at $f = 5$ Hz [18-21]. On the other hand, $f = 5$ Hz was the minimal excitation frequency in the measurement setup used.

Table 1 includes some quantities chosen for comparison ("figures of merit"). Satisfactory agreement of modelled and measured counterparts was achieved for higher excitation levels i.e. approaching saturation in both cases. The discrepancy for modelled loss density did not exceed 18.7%. The discrepancy for coercive field density was of the order 5.3%. However for $B_{\mathrm{m}} = 1.0$ T the discrepancies were considerably higher. Measured loss density was underestimated in both cases, for the rolling direction the discrepancy was -32.6%, whereas for the transverse direction -51.2%. Moreover the modelled value of coercive field strength was significantly lower i.e. -41.5% off the measured value.

Table 1. Some quantities chosen for comparison

f, Hz	B_{m}, T		Loss density *P*, W/kg	Coercive field strength, H_{c}, A/m	Remanence polarization J_{r}, T
5 Hz rolling direction	1.0 T	meas.	0.118	51.1	0.888
		model	0.089	42.2	0.665
	1.5 T	meas.	0.261	61.6	1.414
		model	0.227	63.1	1.362
5 Hz transverse direction	1.0 T	meas.	0.166	71.3	0.681
		model	0.081	41.7	0.396
	1.5 T	meas.	0.343	85.2	1.009
		model	0.279	80.7	0.808

Conclusions

In the paper we have applied the T(x) model combined with the "effective field" to describe quasi-static hysteresis loops for NO steel in two principal directions. We have found out that this approach should rather be applied to narrow hysteresis loops like those exhibited by GO steels. Modeled minor loops were only in qualitative agreement with the experiment for the considered material.

Future work shall be focused on the possibility to include reversible effects into the model equations. We suspect that the refined description may perform somehow better, however in that case the analytical formulation of inverse anhysteretic curve (Eq. (3)) cannot be recovered.

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***Authors**: dr hab. inż. Krzysztof Chwastek, prof. PCz, Politechnika Częstochowska, Katedra Elektroenergetyki, Al. AK 17, 42-201 Częstochowa, E-mail: krzysztof.chwastek@pcz.pl; dr Branko Koprivica/Marko Rosić, Faculty of Technical Sciences Čačak, 32102 Čačak, Serbia; E-mail: branko.koprivica/ marko.rosic@ftn.kg.ac.rs; dr inż. Roman Gozdur, Politechnika Łódzka, Katedra Przyrządów Półprzewodnikowych i Optoelektronicznych, ul. Stefanowskiego 18/22, 90-924 Łódź; E-mail: roman.gozdur@p.lodz.pl; dr hab. inż. Piotr Gębara, prof. PCz, Katedra Fizyki, Al. Armii Krajowej 19, 42-201 Częstochowa, E-mail: piotr.gebara@pcz.pl.*

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