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Modelling the influence of anisotropy on magnetic properties in grain-oriented steels

***Abstract**. The paper presents an anisotropy model of magnetic properties based on the concept of coenergy. The proposed model is verified for chosen grades of grain-oriented electrical steel. It is shown, that it is possible to predict magnetization curves for arbitrary values of angle α on the basis of measurements, made in two directions of sample.*

***Streszczenie.** W artykule przedstawiono model anizotropii właściwości magnetycznych oparty o koncepcję ko-energii. Zaproponowany model został zweryfikowany dla orientowanych blach elektrotechnicznych o wybranych grubościach. Wykazano możliwość uzyskania pętli histerezy dla dowolnego kąta α wycięcia próbki, w oparciu o pomiary wykonane wyłącznie w dwóch kierunkach. (**Modelowanie wpływu anizotropii na własności magnetyczne orientowanej blachy elektrotechnicznej**)*

Keywords: anisotropy, Fröhlich equation, grain-oriented steel, modified elliptic model.
Słowa kluczowe: anizotropia, równanie Fröhlich, orientowana blacha elektrotechniczna, zmodyfikowany model eliptyczny.

Introduction

In order to tailor the operation point of magnetic circuits in electric machines it is necessary to take the anisotropy phenomenon into account [1-4]. Even the so-called isotropic steels can reveal a significant anisotropy [5-7]. There is a number of challenging problems with magnetic measurements carried out under rotational magnetization flux [8-13]. It is thus desirable to focus on these descriptions of magnetization processes, which make it possible to determine the $\vec{B}-\vec{H}$ dependencies at an arbitrary angle from measurements carried out in two orthogonal directions.

There exists a number of engineering approaches to address this issue. As pointed out by Cornut *et al.* [14], some of developed CAD models are not thermodynamically coherent. Péra *et al.* have advanced a relatively simple 2D numerical representation of magnetic properties for anisotropic materials based on coenergy modeling, which is justified from the point of thermodynamics [15]. In their approach, the vector $\vec{B}-\vec{H}$ relationship is equivalent to a contour representation of coenergy density. Recently, the description has been extended by Biró *et al.* [16]. The latter model is the subject of study in the present paper.

Idea of the modified elliptic model

Coenergy density per unit volume is defined as $w'(\vec{H})=\int_0^H \vec{B}(\vec{H})d\vec{H}$. It seems much easier to describe the directional dependences of magnetic properties using the scalar $w'(\vec{H})$ relationship instead of the vector $\vec{B}-\vec{H}$ dependence.

Péra *et al.* [15] have proposed to describe the contours of equal coenergy with an equation similar to the ellipse equation, but the exponent n was different from 2. Their description has been adopted by Biró *et al.* [16] to describe the contours traced by flux density vector for any fixed value of H:

$$\left(\frac{\vec{B}\cdot\vec{e}_1}{B_1(H)}\right)^n+\left(\frac{\vec{B}\cdot\vec{e}_2}{B_2(H)}\right)^n=1, \tag{1}$$

where $\vec{e}_i$ are unit vectors in the rolling (i = 1) and the transverse (i = 2) direction, respectively, whereas H denotes the magnitude of vector $\vec{H}$.

The relationship (1) has to be supplemented with another one, which describes the direction of magnetic field strength ϕ_H, cf. Figure 1.

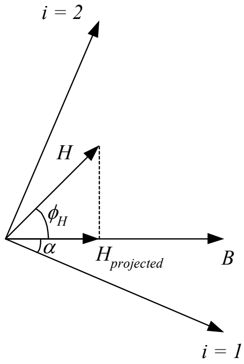

Fig.1. The sketch depicting the considered geometry: α denotes the angle at which the sample was cut off

Biró *et al.* [16] have considered two possibilities for formulation of the second relationship in order to determine the angle ϕ_H, which result from different assumptions on material response in the rolling direction. They have concluded that both alternatives result in similar qualitative behaviour of the description. In the first approach, they have considered the relationship:

$$\vec{B}\cdot\vec{e}_1=B_1\left(\vec{H}\cdot\vec{e}_1\right), \tag{2}$$

what is equivalent to $B\cos\phi_B = B_1(H\cos\phi_B)$. B_1 denotes a functional dependence valid for the rolling direction. The relationship (2) may be interpreted, that permeability in the rolling direction μ_1 is solely the function of magnetic field strength acting in this direction.

The alternative formulation, which is assumed in the present paper, leads to the conclusion, that permeability in the rolling direction is solely the function of flux density

$$\vec{B}\cdot\vec{e}_1=\vec{H}\cdot\vec{e}_1\frac{B}{H_1(B)}, \tag{3}$$

what is equivalent to $H_1(B)\cos\phi_B = H\cos\phi_H$.

Measurements and model verification

The measurements using 25 cm Epstein frame were carried out on two grades of anisotropic steel: 097-30-N5 and 111-35-S5 produced by domestic producer of electrical steel sheets, Stalprodukt SA.

Table 1. Basic magnetic properties of examined steels

Grade	Thickness	Max. loss density @ 1,7 T, 50 Hz	Min. polarization J @ 800 A/m
097-30-N5	0,30 mm	1,50	1,75
111-35-S5	0,35 mm	1,11	1,88

N denotes "normal" steel, S – "special" steel (with reduced loss density)

The samples were cut into stripes 305±0,5mm × 30±0,2mm at different angles from the rolling direction. The measurements were carried out in accordance with the international standard IEC 404-2 part 2 1996-03: Methods of measurement of the magnetic properties of electrical steel sheet and strip by means of an Epstein frame. The excitation frequency was 50 Hz.

The measured $B_m = f(H_m)$ dependencies for the rolling and the transverse directions were fitted with the Fröhlich equation:

$$B = \frac{H}{\alpha + \beta H}\,. \tag{4}$$

The reasons for choice of the the equation for the description were its simplicity and the possibility to invert it, i.e. to express easily the relationship $H_I(B)$.

The model parameters α, β were recovered using least square method applied to the formula (4) after its rectification [17] and are given in Table 2.

Table 2. Parameters of the Fröhlich equation [own research]

Grade 097-30N5		
Parameter	Value	Chosen value
α_1	27,905 ± 9,73429	28
β_1	0,50607 ± 0,00418	0,51
α_2	145,27821 ± 62,06509	100
β_2	0,61072 ± 0,02665	0,62

Grade 111-35S5		
Parameter	Value	Chosen value
α_1	31,87652 ± 10,42645	30
β_1	0,51987 ± 0,00448	0,52
α_2	95,66201 ± 28,83015	100
β_2	0,61779 ± 0,01238	0,62

The modulus of magnetic field strength vector H and the angle ϕ_H were determined from the relationships (1) and (3) using the optimization routines embedded in a commonly-used spreadsheet software (iterative Newton method). The value of coefficient n was kept fixed to 1,4 [16]. The projection of the $\vec{H}$ on the axis of sample magnetization (which in our case was the axis of flux density, $\phi_H = 0$) allowed to recover the dependencies $B_m = f(H_m)$ for directions different from the rolling or the transverse ones. Some of the obtained results are depicted in Figures below.

Discussion

The presented results indicate, that it is possible to recover the approximate shape of $B_m = f(H_m)$ dependence for an arbitrary angle α on the basis of measurements carried out for the rolling and the transverse directions and with the use of the presented coenergy-based description.
The discrepancies between the measured and the modelled $B_m = f(H_m)$ dependencies could result from the approximate character of the Fröhlich equation and from the assumption of fixed value n = 1,4. In some cases, for the values of flux density and magnetic field strength approaching technical saturation, the optimization routine could not yield satisfying results. Future work shall be aimed at solving the issue by consideration of possible variation of n parameter and the use of more accurate descriptions of magnetization curves for the rolling and the transverse directions, which constitute the backbone of the presented model. The application of some other optimization routines, e.g. the robust "branch-and-bound" algorithm [18], useful for solving low-dimensional problems [19], is also taken into account.

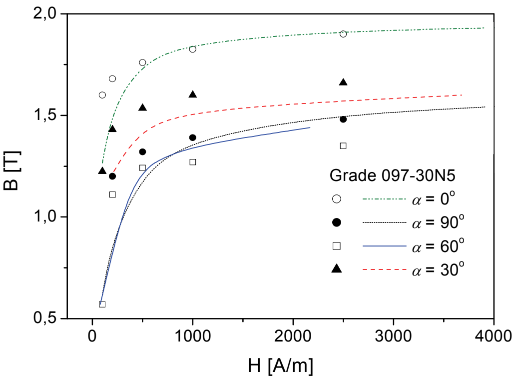

Fig.2. The measured (lines) and the modelled (symbols) $B_m = f(H_m)$ dependencies for arbitrary values of angle α [own research]

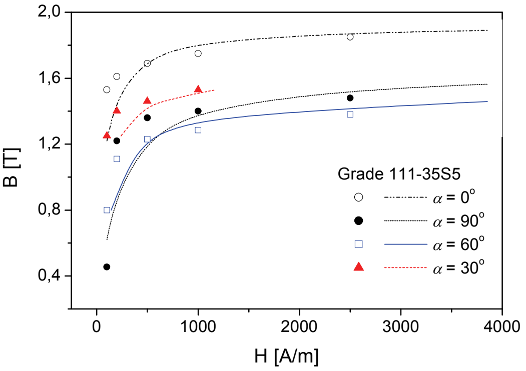

Fig.3. The measured (lines) and the modelled (symbols) $B_m = f(H_m)$ dependencies for arbitrary values of angle α [own research]

A natural step forward is to consider a coupling of the presented description with another coenergy-based model of mechanical and magnetic properties in electromechanical transducers [20] in order to develop a more precise model of the transducer, able to take into account its anisotropic magnetic properties.

Conclusion

An anisotropy model based on coenergy considerations has been presented and verified for chosen grades of electrical steel. It is shown, that it is possible to predict the $B_m = f(H_m)$ dependencies for arbitrary values of angle α on the basis of magnetic measurements carried out only for the rolling and the transverse directions. The model reproduces correctly the typical behaviour of anisotropic steel – the worst magnetic properties are obtained for α close to 60°. The proposed description is easier in implementation than the existing models of rotational losses. It also allows us to avoid troublesome measurements for intermediate directions of samples.

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