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ANISOTROPIC PROPERTIES OF DYNAMO STEEL SHEETS

ANIZOTROPOWE WŁAŚCIWOŚCI BLACH PRĄDNICOWYCH

Abstract

The paper deals with the anisotropic properties of typical dynamo steel sheets. The cause of the magnetic anisotropy is the occurrence of certain textures in the dynamo sheets. The most frequently occurring types of textures in these sheets are briefly described. For a few selected dynamo sheets, values of the typical magnetic parameters for different directions of magnetization processes are presented. The paper proposes a method, which allows us to take into account the anisotropic properties of dynamo sheets in calculations of flux density changes during both the axial and rotational magnetization. A specially selected function of the grain distribution in the given dynamo sheet allows taking into consideration the anisotropic properties. Examples of the flux density changes during the axial and rotational magnetization are presented in the end part of the paper.

Keywords: dynamo steel sheet, hysteresis loop, magnetic anisotropy

Streszczenie

Artykuł dotyczy anizotropowych właściwości typowych blach prądnicowych. Przyczyną anizotropii magnetycznej takich blach jest występowanie w nich pewnych tekstur. Krótko scharakteryzowano typy tekstur najczęściej występujące w tych blachach. Dla kilku wybranych blach prądnicowych przedstawiono wartości typowych parametrów magnetycznych dla różnych kierunków magnesowania. Zaproponowano metodę uwzględnienia anizotropowych właściwości blach prądnicowych w obliczeniach zmian indukcji podczas przemagnesowania osiowego i obrotowego. Specjalnie dobrana funkcja rozłożenia ziaren w danej blasze pozwala uwzględnić anizotropowe właściwości w obliczeniach zmian indukcji. Przykłady zmian indukcji podczas przemagnesowania osiowego i obrotowego przedstawiono w końcowej części artykułu.

Słowa kluczowe: anizotropia magnetyczna, blachy prądnicowe, pętla histerezy

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1. Introduction

Dynamo steel sheets are mainly applied in magnetic circuits of rotating machines, but quite often they are also used in magnetic cores of small power transformers. Therefore, these sheets should have the same magnetic properties in each direction on the sheet plane. Grains in the dynamo steel sheets are very small, their average size is in the range from about 20 μm to about 100 μm, and the distribution of grains in isotropic (non-oriented) sheets should be the same with respect to all directions. However, magnetic measurements carried out by means of both the RSST device and the Epstein frame have shown that the majority of the dynamo steel sheets have certain anisotropic features. As a result, the anisotropic properties of the dynamo sheets have a certain influence on the magnetic flux distribution in the magnetic cores of electrical machines and transformers [1, 2]. Crystallographic research, performed for several typical dynamo sheets with the use of the X-ray diffractometer, has shown that an amount of the sheet grains has a certain texture (privilege crystallographic orientation). The volume part of the individual texture is in the range from a few to over twenty percent of the whole sample volume of the given dynamo sheet.

Changes of the flux density in electrical steel sheets depend not only on the field strength value, but they also depend on the texture types, which can occur in these sheets. Various technological procedures in the manufacturing process of dynamo steel sheets are designed to achieve texture-free(non-oriented) materials, but these sheets have not been produced so far on an industrial scale.

Textures in dynamo sheets are also the reason of the anisotropy, which refers to power losses during magnetization processes. Due to the occurrence of certain crystallographic orientations, hysteresis loops measured along different directions on the sheet plane differ from each other. As a result of this, the hysteresis losses depend on the direction of the magnetization process; this problem is discussed in [3–6].

Dynamo steel sheets can be magnetized in different directions. First of all, it refers to the magnetic cores of the rotational machines, although in magnetic circuits of transformers the magnetic flux can also change its direction. For example, this case can occur during a current overload when the permeability of the magnetic circuit decreases strongly. So, in many cases it is necessary to calculate the magnetic field distribution for different directions of the magnetic flux. This is possible using an appropriate model of the magnetization process, which allows us to take into account anisotropy properties of the dynamo steel sheets. The method of the modelling of magnetization processes in soft magnetic materials is widely presented in [7].

The anisotropic properties of the dynamo steel sheets are discussed on the basis of four selected sheets coming from different manufacturers. In order to assess the anisotropy of these dynamo sheets, special crystallographic studies were carried out; they have shown an occurrence of certain textures in these sheets. Additionally, magnetic measurements of the axial magnetization along some directions on the sheet plane were performed. Results of the texture analysis were used in order to take into account the anisotropic properties in the author's model of the rotational magnetization.

2. Typical textures of dynamo steel sheets

Studies concerning textures in dynamo sheets were carried out for some typical sheets with the thickness of 0.5 mm by means of the X-ray diffractometer [8]. The textures were determined by the interpretation of X-ray diffraction patterns, which were obtained for the radiation with an energy of 30 keV passing through the dynamo sheets[1]. In this research, the stereographic projections are performed and the reflections from the selected crystallographic plane of the given dynamo sheet sample are counted. Points with the same intensity of reflections are connected by lines. It allows obtaining the so-called pole figures, which make possible the description of the texture type in electrical steel sheets. The intensity of reflections in the pole figures gives the possibility to estimate the volume of a privileged crystallographic orientation.

The diffraction patterns concerning the lattice planes type {100}, {110} and {111} of the iron crystal allow interpretation of the six known fibres of the rolling and the recrystallization texture of the ferritic steel. All six fibres are involved in creation of diffractions from the plane {110}. However, diffractions from the planes {100}, {111} do not have complete information about textures and these diffractions have a secondary meaning. For texture tests, the following dynamo sheets were selected: M400-50A, M800-50A (both produced in Sweden), M530-50A (Czech Republic), and M530-50A (South Korea). Figure 1 presents, for example, the pole figures of the dynamo sheets M400-50A and M530-50A (Czech Republic). The pole figures of the sheet M800-50A and of the Korean sheet M530-50A are similar to the pole figures presented in Figure 1a and 1b, respectively.

It is obvious that all grains in any dynamo sheet should be distributed evenly. However, texture studies have shown that in these sheets a certain amount of grains has a privilege crystallographic orientation. The analysis of the diffraction patterns indicates that in the sheets type M400-50A and M800-500 the following textures occur first of all: {100}<056>, {100}<049>, {111}<11$\bar{2}$>, {111}<3 4$\bar{7}$>. These symbols indicate which crystallographic planes and directions of the cubic-shaped iron crystals are parallel to the sheet plane and to the rolling direction [8]. The two first crystallographic orientations refer to the so-called cubic texture in which two of six walls of the iron crystal are arranged parallel to the sheet plane. It causes the same magnetization properties in two mutually perpendicular directions on the sheet plane; however, these orientations usually differ with respect to the rolling direction. Other types of the mentioned textures indicate that all three easy magnetization axes of the iron crystal are inclined to the sheet plane at an angle of 45 degrees, and the planes {111} are parallel to the sheet plane. These planes are determined by three points of the cubic-shaped iron crystal, which do not belong to the same crystal wall. In this case, the same magnetization properties occur every 120 degrees on the sheet plane. It should be stressed that flux density changes on the sheet plane depend on all texture types and on remaining randomly distributed grains in the given dynamo sheet. In the other two tested sheets type M530-50A (Czech Republic and South Korea) the texture type {110}<1$\bar{1}$1> occurs in addition to the above-mentioned textures. It means that two of six easy

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[1] Crystallographic research was performed in the Institute of Non Ferrous Metals in Gliwice, Light Metal Division in Skawina (Poland).

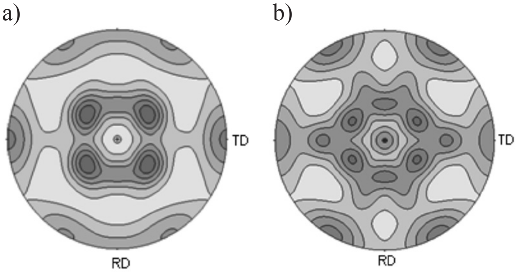

Fig. 1. Pole figures {110} of the dynamo sheet: a) M400-50A, b) M5300-50A (Czech Republic); intensity scale is linear, RD – rolling direction, TD – transverse direction

magnetization axes of the cubic-shaped iron crystal are parallel to the sheet plane, but these two axes are usually not parallel to the rolling direction.

Determination of the volume fraction of the given texture in the sheet sample is not an easy task in crystallography. Special software for the analysis of the pole figures, developed in the research centres, allows estimation of the volumetric amount of individual textures occurring in the given dynamo sheet. The share of individual textures is not high (in comparison to the transformer sheets), but in some cases this share is even over twenty percent of the total volume of the given sheet sample. It is worth underlining that research concerning textures indicates that grains are distributed symmetrically relative to both the rolling and the transverse directions [9, 10].

The occurrence of different textures in the dynamo steel sheets is the main cause of their anisotropic properties. These properties are different for particular dynamo sheets and have a significant impact on the magnetic parameters of these sheets that strongly depend on the magnetization direction. Magnetic measurements have allowed the authors to present dependences of the flux densities on the magnetization direction; it is presented in detail in the next Chapter. Determination of the volume fraction of a dominant texture in the given tested dynamo sheet was used by the authors to take into account the sheet anisotropy in the model of the rotational magnetization (Chapter 4).

3. Magnetic anisotropy in typical dynamo steel sheets

Measurements of magnetization curves were carried out by means of the Epstein frame[2]. Hysteresis loops were measured in different directions at every 15 degrees with respect to the rolling direction. The measurement results have shown that all tested dynamo sheets have anisotropic properties, although in various degrees. Characteristic magnetic parameters measured for three angles between the magnetization and the rolling direction are presented in Table 1. In turn, Figure 2 presents the dependence of the flux density maximum values on the angle between the given direction on the sheet plane and the rolling direction. The

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[2] Measurements were carried out in the Laboratory of Magnetic Measurements (Stalprodukt S.A.) in Bochnia (Poland).

influence of the magnetic anisotropy on the flux density maximum value is lesser when the value of the field strength increases. This is because the process of the domain wall motion ends and the resultant flux density vectors of the particular grains begin to rotate towards the direction of the field strength [11, 12].

Table 1

Characteristic magnetic parameters of selected dynamo sheets for three assumed maximum values of the flux density

Type of sheet				**M120-27S**			**M110-23S**			**M120-30S**		
Conductivity $[(\Omega*m)^{-1}]$ $*10^6$				2.13			1.64			2.38		
Flux density [T]				1.0	1.5	1.7	1.0	1.5	1.7	1.0	1.5	1.7
Eddy current losses 100 Hz 0.360			50 Hz	0.090	0.202	0.259	0.041	0.092	0.118	0.115	0.259	0.333
			0.808	1.036	0.164	0.368	0.472	0.460	1.036	1.332		
Excess losses	0°	meas.	50 Hz	0.140	0.295	0.385	0.136	0.288	0.409	0.104	0.222	0.260
		estim.	50 Hz	0.139	0.296	0.373	0.144	0.310	0.392	0.106	0.226	0.285
		meas.	100 Hz	0.448	0.948	1.159	0.464	0.950	1.229	0.310	0.664	0.775
		estim.	100 Hz	0.410	0.852	1.066	0.499	0.982	1.207	0.326	0.695	0.876
	15° measured 100 Hz		50 Hz	0.203	0.474	0.681	0.168	0.456	0.734	0.187	0.424	0.613
			0.624	1.362	1.862	0.548	1.359	2.002	0.551	1.188	1.635	
	30° measured 100 Hz		50 Hz	0.365	1.049	1.349	0.252	0.816	1.361	0.310	0.889	1.585
			1.051	2.663	4.094	0.783	2.205	3.501	0.899	2.317	3.906	
	45° measured 100 Hz		50 Hz	0.678	2.039	1.924	0.554	1.831	1.401	0.638	2.088	1.998
			1.796	5.011	4.989	1.536	4.555	3.676	1.671	4.954	4.304	

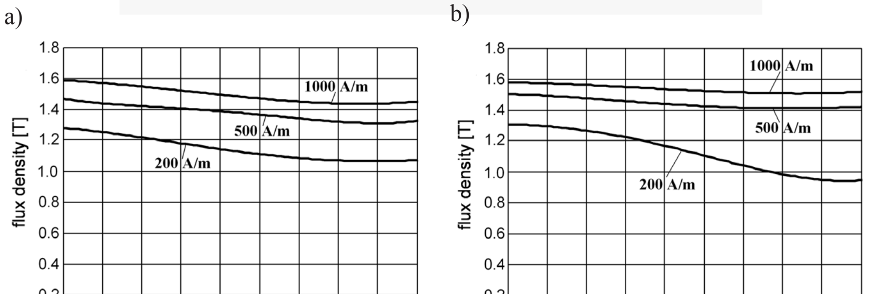

Fig. 2. Maximum values of the flux density as the dependence on the angle of the field strength direction: a) M530-50A (Czech Republic), b) M800-50A

The influence of the anisotropy on the magnetic properties is more noticeable when we present the remanence (residual flux density) as the dependence on the angle of the field strength direction. Similarly, as previously, Figure 3 shows the remanence values as a function of the angle between the given direction and the rolling direction for some values of the field strength.

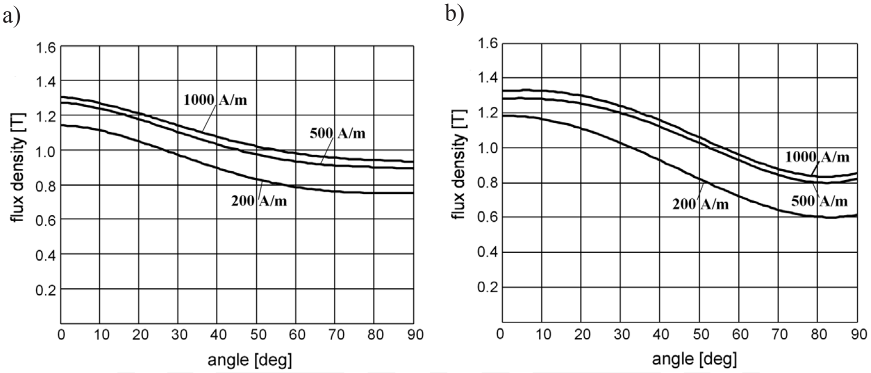

Fig. 3. Remanence values as the dependence on the angle of the field strength direction: a) M530-50A (Czech Republic), b) M800-50A

The highest values of the remanence occur along the rolling direction. However, in the range close to the transverse direction the remanence values are even 50 per cent lesser with respect to the rolling direction. It has an impact on the flux density values, especially when the field strength is lesser than 100 A/m for typical dynamo sheets.

4. Inclusion of the magnetic anisotropy in magnetization process model

Methods allowing engineers to take into calculations the anisotropy of the electrical steel sheets have been already presented in several papers. About 20 years ago, the so-called elliptical model of the magnetic anisotropy [13] and the model based on the co-energy density [14, 15] were proposed, however, these proposals concerned non-hysteresis materials. Sometimes the magnetic anisotropy of electrical steel sheets is taken into calculation using the reluctivity or permeability tensor [16, 17]. Quite often, this problem is being solved by appropriate modification of a chosen vector hysteresis model. A proposal how to take the magnetic anisotropy of electrical steel sheets is described in [18], but the presented method is based on an artificial change of the field strength with respect to the different directions on the given sheet plane.

The method which allows us to take into account the magnetic anisotropy of the dynamo steel sheets was presented by the authors in a simplified form in Proceedings of the Conference EPNC"2012, whereas the extended version of this method is described in [10]. This paper presents how to take into calculations the texture types which occur in the given dynamo sheet.

In order to take into calculations the anisotropy, the author's model of the rotational magnetization described in [7] is used. In this model, the plane of a sample of an anisotropic sheet is divided into an assumed number of specified directions. For engineering purposes, the anisotropic properties can be taken into account with the assumption that all grains are the same and they have one easy magnetization axis, as it was suggested in [19]. Due to the magnetic anisotropy, to each individual direction a different number of grains (whose easy magnetization axis is parallel to the given direction) is assigned (Fig. 4). Assuming that the sample of the given dynamo sheet is divided on 12 directions, the distribution of the grains can be described by means of the so-called grain distribution function $d(k)$:

$$d(k) = d_1, d_2, \ldots, d_k, \ldots, d_{11}, d_{12} \tag{1}$$

where:

d_k – relative amount of grains that are assigned to the k-th direction.

The sum of all function values must be equal to 1. For the example which is shown in Figure 4, the grain distribution function has the following values:

$$d(k) = 0.01 \cdot (6, 7, 7, 7, 10, 10, 12, 10, 10, 7, 7, 7) \tag{1a}$$

The determination of the values of the grain distribution function is not easy. These values are estimated with the use of special software applied in crystallography, which enables us to determine the volumetric amount of this texture in the given dynamo sheet sample [8].

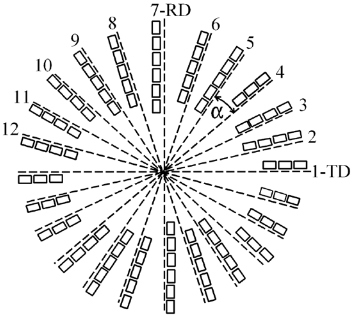

Fig. 4. Simplified distribution of grains in a certain sheet: RD, TD – rolling, transverse direction, respectively

Usually it is assumed that the grains of the most privileged orientation are arranged in accordance with the Gaussian distribution, and remaining grains are distributed randomly. However, it should be noted that quite often the final correction of these values is carried out by means of the trial-and-error method.

In the used model of the magnetization process, a certain hysteresis loop (the so-called direction hysteresis) is assigned to each specified direction on the dynamo sheet plane (Fig. 5). These direction hystereses are described by such parameters as: saturation flux density b_{sk}, remanence (residual flux density) b_{rk}, and coercive force h_c. It is necessary to underline that these parameters and direction hystereses cannot be measured and they differ from the hysteresis of the whole sheet sample. The parameters of the direction hystereses are calculated on the basis of measurements of the limiting and some partial hysteresis loops. In numerical calculations, the hysteresis model based on an exponential function has been used [20].

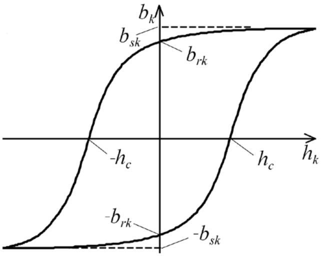

Fig. 5. Example of the direction hysteresis

Determination of the direction hysteresis parameters is presented in detail in [7]; this paper presents only the basic formulas. In the saturation state, the resultant flux density B_s of the whole sheet sample is an algebraic sum of the saturation flux densities of all direction hystereses. The saturation flux density b_{sk} for the given k-th direction equals:

$$b_{sk} = d_k \; B_s \tag{2}$$

where:

B_s – saturation flux density (determined by measurements) of the dynamo sheet.

When the field strength is decreased from the saturation state to zero, then the resultant flux density of the given sheet sample is equal to the remanence B_r of the given dynamo sheet. The flux density vectors of the direction hysteresis lie along individual directions and the lengths of these vectors are equal to the remanences b_{rk} of the direction hysteresis. The remanence b_{rk} of the individual direction hysteresis is equal to the $b_{rz} d_k$ product:

$$b_{rz} = \frac{B_r}{d_2 \cos 5\alpha + d_3 \cos 4\alpha + \ldots + d_7 + \ldots + d_{12} \cos 5\alpha} \tag{3}$$

where:

B_r – remanence measured with respect to the rolling direction,

α – angle between two neighbouring directions (Fig. 4).

When the field strength H changes in the opposite direction to the saturation state then the flux densities b_k of the direction hysteresis decrease, and the points with the coordinates (h_k, b_k) move along the left curves of the direction hysteresis loops. If we assume that the dependence between the flux density b_k and the field strength h_k is linear in a quite wide range we can prove that the coercive force h_c of the direction hysteresis equals:

$$h_c = H_c \frac{b_{r2} \cos^2 5\alpha + b_{r3} \cos^2 4\alpha + \ldots + b_{r7} + \ldots + b_{r12} \cos^2 5\alpha}{b_{r2} \cos 5\alpha + b_{r3} \cos 4\alpha + \ldots + b_{r7} + \ldots + b_{r12} \cos 5\alpha} \tag{4}$$

where:

H_c – coercive force of the dynamo sheet with respect to the rolling direction.

The values of the grain distribution function have not occurred in the last relation. However, the coercive force h_c depends on this function because the remanences of the direction hystereses are dependent on the d_k values.

It is necessary to underline that for relatively low values of the field strength only domain wall movements occur in the grains of the dynamo sheets. For higher values of the field strength, the flux density vectors rotate towards the field strength direction. New positions of the flux density vectors can be determined on the basis of the energy minimum condition. However, numerical calculations have shown that the angles of these rotations are not greater than two to three degrees if the amplitudes of the field strength are not higher than 500 A/m. Thus, the rotations of the flux density vectors can be neglected in the considered cases of the magnetization process in the dynamo steel sheets.

In numerical algorithm, for the given vector of the field strength the vector projections on the specified directions are calculated. In the next step, the flux densities in the individual directions are determined on the basis of the direction hystereses. The resultant flux density in the elementary sheet sample is the vector sum of the flux densities in the specified directions. For the next field strength vector (with a new value and position), the projections of this vector of the individual directions are determined again. Then the flux density changes in the specified directions and new resultant values of the flux density in the given sheet sample can be calculated.

5. Influence of the anisotropy on flux density changes

As it was previously mentioned, dynamo steel sheets are applied also in magnetic circuits of small power transformers. In some parts of the given transformer sheet the magnetic flux is parallel to the rolling direction, but in other parts, the same magnetic flux is parallel to the transverse direction. It is worth underlining that in the corners of the transformer magnetic circuits, the magnetic flux has usually a different angle with respect to both the rolling and transverse directions. Additionally, in the *T*-points of three-phase transformer cores, the magnetization process can have a rotational character with a certain small elliptical degree. Therefore, the calculations of the magnetic field distribution in magnetic circuits, which are made from anisotropic dynamo sheets, should be carried out using the model of the rotational magnetization. The previously described model allows us to obtain correct calculation results independently of the field strength direction. The experimental verification of this model was presented in [21]. It is necessary to stress that the model of the rotational magnetization can also be used in calculations of the axial magnetization.

Numerical calculations were performed for two selected dynamo sheets. The first one was the sheet M800-50A with the following parameters: saturation flux density – 1.98 T, remanence – 1.15 T, and coercive force – 80 A/m, and the second one was the sheet M530-50A (produced in Czech Republic) with the parameters, which are equal to 1.95 T, 1.10 T, and 70 A/m, respectively. The values of the grain distribution function for the first sheet were equal to: 6, 6, 7, 7, 8, 12, 14, 12, 8, 7, 7, 6 and for the second sheet: 6, 5, 6, 7, 9, 13, 13, 13, 9, 8, 6, 5 respectively. The calculated hysteresis loops were compared with the hysteresis loops obtained on the basis of the measurements (Fig. 6). Differences between hysteresis loops are the result of the magnetic anisotropy which is caused by the occurrence of the privileged orientations of a certain amount of grains in the majority of typical dynamo steel sheets.

The magnetic anisotropy influences the flux density changes also during the rotational magnetization. When the given dynamo sheet has anisotropic properties then the hodographs of flux density changes during rotational magnetization (with a constant value of the field strength) do not have a circular shape. For example, the calculated hodographs of the flux density for three values of the field strength are presented in Figure 7. For increasing values of the field strength, these hodographs are more and more similar, because the rotations of the resultant flux density vectors of the individual grains begin to have the major contribution to the magnetization process.

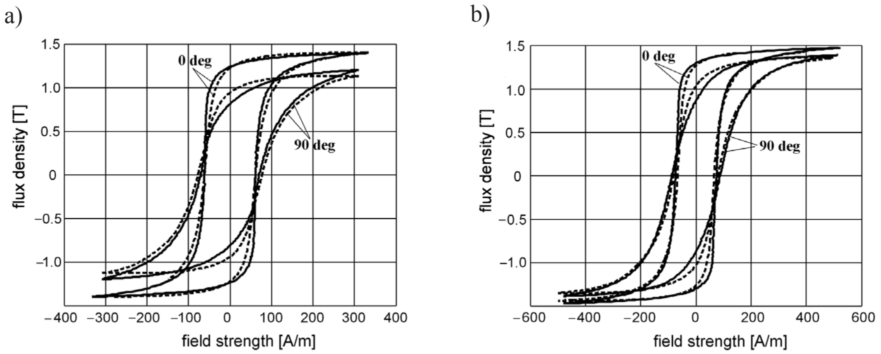

Fig. 6. Hysteresis loops for the rolling direction (0 deg) and transverse direction (90 deg): a) M530-50A (Czech Republic), b) M800-50A; continuous lines – measured loops, dashed lines – calculated loops

It should also be noted that the lag angle of the flux density depends on the field strength value. Figure 8 shows hysteresis loops measured and calculated with respect to the rolling direction (RD), and transverse direction (TD) during the rotational magnetization [22].

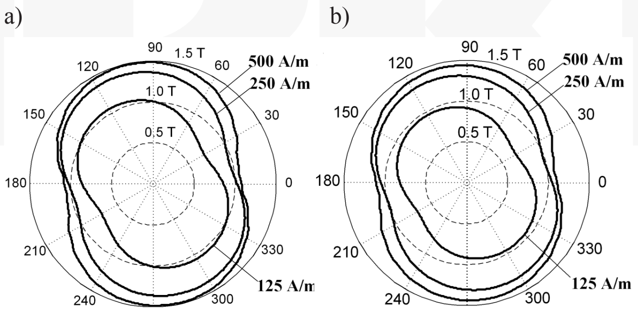

Fig. 7. Hodographs of the flux density during the rotational magnetization for three assumed values of the field strength: a) M530-50A (Czech Republic), b) M800-50A

It is worth mentioning that the shape of these loops differs significantly from the well-known shape of the hysteresis loop during the axial magnetization. Due to the anisotropic properties, the maximum values of the flux density are higher than the corresponding values of the flux density determined in the transverse direction.

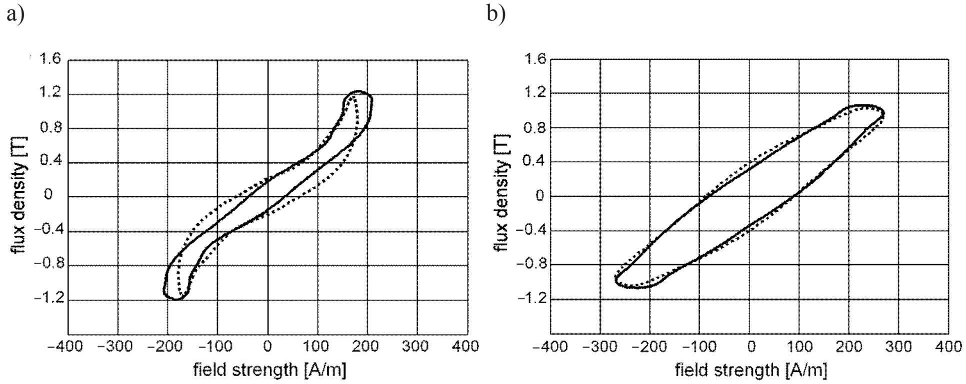

Fig. 8. Hysteresis loops during the rotational magnetization of the dynamo sheet M530-50A (Czech Republic) along: a) the rolling direction RD, b) transverse direction TD; continuous lines – measured loops, dotted lines – calculated loops

6. Conclusions

This paper briefly presents the influence of the magnetic anisotropy on the magnetization processes in typical dynamo sheets. This anisotropy can cause quite significant differences between magnetization processes, which occur in different directions on the sheet plane. Changes of the flux density depend not only on the value and direction of the field strength, but also they depend on the occurrence of the privileged orientations of grains in the given dynamo sheets. It has a significant meaning when the field strength can change its direction on the sheet plane, especially during the rotational magnetization.

The magnetic anisotropy of the dynamo sheets is taken into account with the use of the grain distribution function. Thus, the parameters of the direction hystereses depend on this function values. For simplification, it was assumed that all grains in dynamo sheets have only one easy magnetization axis. However, the cube-shaped grains of iron have three easy magnetization axes; therefore, the comprehensive model of the magnetization process should consider three easy magnetization axes, and magnetization processes occurring along these axes.

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