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Influence of magnetic anisotropy on flux density changes in dynamo steel sheets

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Abstract: Magnetic measurements, carried out by means of the Epstein frame, have shown that most typical dynamo steel sheets have certain anisotropic properties. In numerical analysis, anisotropic properties are taken into account with the use of the special function of the grain distribution in the given dynamo sheet. For engineering purposes, it is desirable to assess the influence of these properties on the changes of the magnetic flux density in typical dynamo steel sheets, especially during the rotational magnetization. For this purpose, measurements of the flux density changes and field strength changes in the circular-shaped samples of two selected typical dynamo sheets were performed. These measurements were carried out for several values of the current flowing in windings which generated the axial or rotational magnetic field in the test dynamo sheet. The influence of the magnetic anisotropy on the magnetization process was briefly discussed for both types of the magnetization processes.

Key words: anisotropic properties, dynamo steel sheet, magnetization process, rotational magnetization

1. Introduction

Dynamo steel sheets are used mainly in constructions of stators and rotors of induction and synchronous machines. Magnetization processes in magnetic circuits of these machines can have a different character. In the stator cores the magnetization process has usually rotational character, mainly elliptical, whereas in stator teeth this process has frequently axial character.

Depending on applications, dynamo sheets can be magnetized in different directions. Therefore, these sheets should have isotropic properties, and they are produced as non-oriented steel sheets. However, different magnetic measurements carried out by means of both the Epstein frame and the Rotational Single Sheet Tester have shown that dynamo sheets have certain anisotropic properties, both in terms of the magnetization curves and power losses [1, 2]. The magnetic anisotropy occurring in the majority of dynamo steel sheets should be taken into numerical models of the magnetization processes, especially in analysis of the rotational magnetization. It is worth noting that dynamo sheets are quite often used in the construction of cores of small power transformers. From these sheets different shapes for transformer cores are cut out. Worse magnetic properties in the transverse direction with respect to the rolling direction of the given dynamo sheets cause the value of the total magnetic flux in a transformer core to decrease.

2. Taking anisotropic properties into consideration

Methods which allow us to take into considerations the anisotropic properties of transformer or dynamo steel sheets have already been presented in several papers. The so-called elliptical model of the magnetic anisotropy [3] and the model based on the co-energy density [4, 5] were proposed. However, these proposals concerned non-hysteresis materials. In some studies**,** the magnetic anisotropy of electrical steel sheets have been taken into account using the reluctivity or permeability tensor [6].

The anisotropic properties of a dynamo sheet can quite easily be taken into account in the model of the rotational magnetization which is described in detail in [7, 8]. The plane of a sample of the given dynamo sheet is divided into an assumed number of specified directions, as it is proposed in [9]. To each specified direction on the sheet plane, the so-called direction hysteresis is assigned, which differs from the hysteresis of the whole anisotropic sheet sample. Parameters of the direction hystereses like the saturation flux density, the residual flux density and the coercive force are determined analytically on the basis of magnetic measurements performed for the whole sheet sample.

Due to the sheet anisotropy, a different amount of iron grains is assigned to each specified direction. For engineering purposes, the anisotropic properties can be taken into calculations with the assumption that all grains are the same and these grains have only one easy magnetization axis, as it was suggested in [10]. To each individual direction a different number of grains (whose easy magnetization axis is parallel to a given direction) is assigned (Fig. 1). Assuming that the sample of the given dynamo sheet is divided on 12 directions, the arrangement of 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 denotes the relative amount of grains which are assigned to the k-th direction; the sum of all d_k values must be equal to 1. For the example which is shown in Figure 1, the grain distribution function has the following form

$$d(k) = 0.01 \cdot (6, 7, 7, 7, 10, 10, 12, 10, 10, 7, 7, 7). \tag{2}$$

The determination of the values of the grain distribution function is quite difficult. These values are estimated with the use of special software applied in crystallography, which enables us to determine the volumetric amount of a certain texture in the given generator sheet sample [11]. 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.

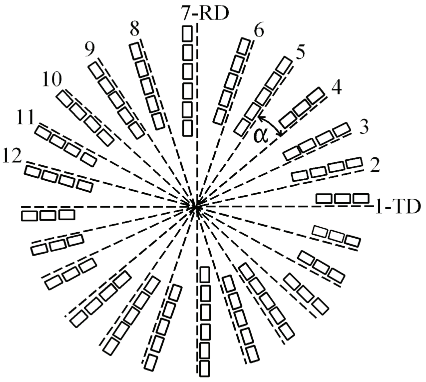

Fig. 1. Simplified drawing of the grain distribution in a certain anisotropic dynamo sheet: rolling direction (RD) and transverse direction (TD)

The parameters of the direction hysteresis depend on the grain distribution function describing the grain arrangement in the given dynamo sheet. It should be stressed once again that these parameters and direction hystereses cannot be measured. The parameters of the direction hystereses are calculated on the basis of the measurements of the limiting loop and some partial hysteresis loops. Determination of these parameters was widely discussed in [7]. It is understood that in order to obtain correct results of numerical calculations, the model of the rotational magnetization which takes into account the anisotropic properties must be included in the equations of the magnetic field and eddy current field distribution, and it is described in [12].

Studies were performed for two selected dynamo sheets marked as M530-50A; the first one is produced in the Czech Republic, and the second one is manufactured in South Korea. On the basis of crystallographic measurements[1], we have assumed that the grain distribution functions have the following form:

– for Czech dynamo sheet

$$d(k) = 0.01 \cdot (7, 7, 8, 9, 9, 10, 7, 10, 9, 9, 8, 7), \tag{3}$$

– for Korean dynamo sheet

$$d(k) = 0.01 \cdot (7, 8, 9, 9, 9, 8, 7, 8, 9, 9, 9, 8). \tag{4}$$

3. Influence of anisotropic properties on the axial magnetization

The magnetization process in stator teeth of induction or synchronous machines has axial character first of all. Changes of the flux density in particular teeth depend on the angle between the axis of the given tooth and the rolling direction of the considered dynamo sheet. It is well known that flux density changes in an anisotropic sheet depend on the direction of the

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

field strength changes. Measurements of the axial magnetization were carried out by means of the Epstein frame for sheet strips which were cut out at different angles with respect to the rolling direction. Table 1 presents, for example, characteristic values of both test dynamo sheets, where H_{sat} denotes the saturation field strength at 1.8 T, B_r is the residual flux density, and H_c presents the coercive force. The angle 0° corresponds to the rolling direction of the given dynamo sheet.

Table 1 Characteristic parameters of the test dynamo sheets

Magnetization angle	**Czech dynamo sheet**			**Korean dynamo sheet**		
	H_{sat} [A/m]	B_r [T]	H_c [A/m]	H_{sat} [A/m]	B_r [T]	H_c [A/m]
0°	8088	1.32	64	7587	1,22	70
45°	10570	1.02	76	11062	1.05	78
90°	10490	0.92	78	9523	0.79	85

The magnetic anisotropy (and also the anisotropy of power losses) is caused by the occurrence of certain textures; it is a characteristic property of most dynamo steel sheets. It should be noted that relevant standards define the acceptable anisotropy of the power losses in the range from 10 to 14%. Figure 2 presents hysteresis loops of two above mentioned sheets[2]. Hysteresis loops measured for 45° are similar to the loops obtained for 90°.

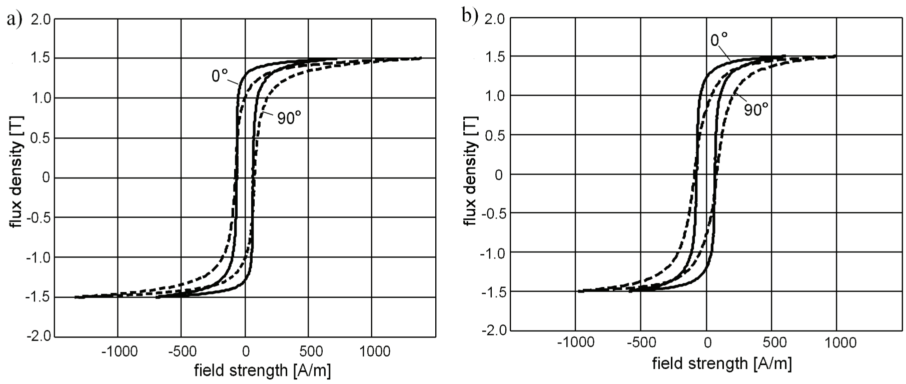

Fig. 2. Hysteresis loops of: a) Czech dynamo sheet, b) Korean dynamo sheet

Differences between values of the residual flux density are about 18 per cent in the case of the Czech dynamo sheet; for the Korean sheet these differences are significantly bigger. Magnetic measurements and corresponding numerical calculations have shown that relevant differences between the flux density values which were determined for the rolling direction and the transverse direction occur when the field strengths are less than 200 to 300 A/m. If the

[2] Magnetic measurements were carried out in Laboratory of Magnetic Measurements in Stalprodukt SA, Bochnia (Poland).

field strength values are bigger than 300 A/m, the flux densities in typical dynamo sheets increase more slowly, and the differences of the magnetization characteristics are getting smaller.

4. Influence of the anisotropy on the rotational magnetization

As it was previously mentioned, dynamo steel sheets are produced as non-oriented sheets, and therefore they should have isotropic properties. It means that hodographs of the flux density or field strength during the rotational magnetization should have a circular shape. However, due to anisotropy which occurs in the majority of typical dynamo sheets, hysteresis loops measured along different directions on the sheet plane differ from each other.

Magnetic measurements were carried out with the use of a laboratory stand, which was constructed on the basis of the stator of a typical induction motor of 5 kW. Two sinusoidally distributed windings were placed on the stator in two mutually perpendicular axes. Two coils for indirect determination of the flux density and two coils for determination of the field strength were mounted on the test dynamo sheet, as it is applied in existing methods of magnetic measurements during the rotational magnetization [2, 9]. The circle-shaped sample with a thickness of 0.5 mm of the given dynamo sheet was placed in the middle of the stator. Additionally, two sheet packets, each consisting of five sheets, were placed on both sides of the test sheet sample (Fig. 3). These additional sheet packages provide a more uniform distribution of the magnetic field in the given sheet sample.

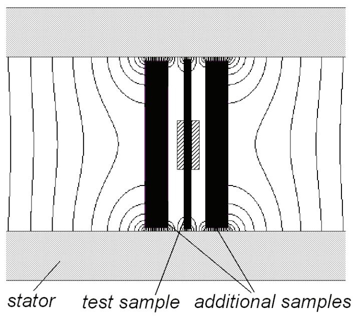

Fig. 3. Pictorial drawing of the measurement system; lines present the magnetic field distribution in the cross-section of the measurement system

Measurements were performed by providing several sinusoidal currents in the windings which generate a rotational field inside the test dynamo sheet. Figure 4 shows examples of the hysteresis loops during rotational magnetization, measured along the rolling direction (RD), and analogous loops measured along the transverse direction (TD). These loops were obtained for three values of the current flowing in the windings. It is necessary to stress that the shapes of these loops differ significantly from the shapes of the hysteresis loops during the axial magnetization. Due to the magnetic anisotropy, the maximum values of the flux density are higher than the corresponding values determined for the transverse direction, but these differences are insignificant. The influence of the magnetic anisotropy on the rotational magnetization can be clearly seen in the example of the changes of the flux density amplitude as a dependence on the magnetization angle. Figure 5 presents changes of the flux density and changes of the field strength during rotational magnetization in the Czech dynamo sheet, and analogous waveforms for the Korean sheet are shown in Figure 6. Measurements were carried out for two frequencies of 50 Hz and 100 Hz. For isotropic dynamo sheet the amplitude of the flux density and the amplitude of the field strength during rotational magnetization should have constant value. Due to the anisotropic properties both amplitudes are not constant; it can be especially observed for the field strength changes. The influence of the magnetic anisotropy on the field strength changes is significant when flux density values are higher than about 1.2 T, because then the process of domain wall movements ends. However, for engineering purposes, changes of the flux density amplitude as a function of the magnetization angle are more important than changes of the magnetic field strength. It is worth noting that the influence of the frequency on the flux density changes is insignificant.

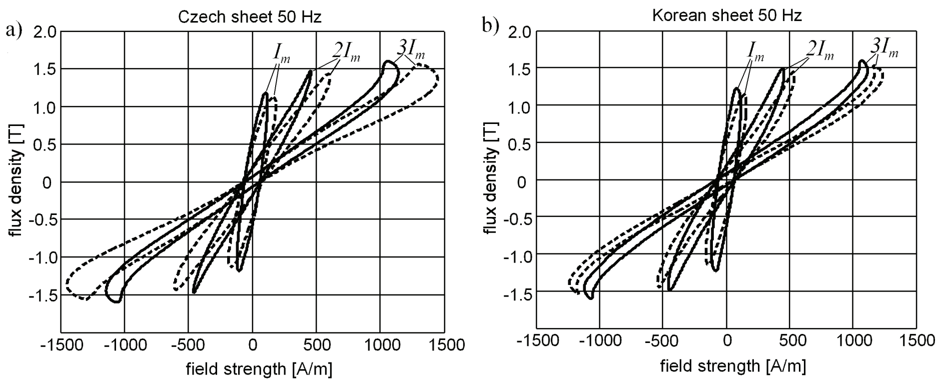

Fig. 4. Hysteresis loops measured during rotational magnetization: a) Czech dynamo sheet, b) Korean dynamo sheet; continuous lines – loops measured along the rolling direction (RD), dotted lines – loops measured along the transverse direction (TD)

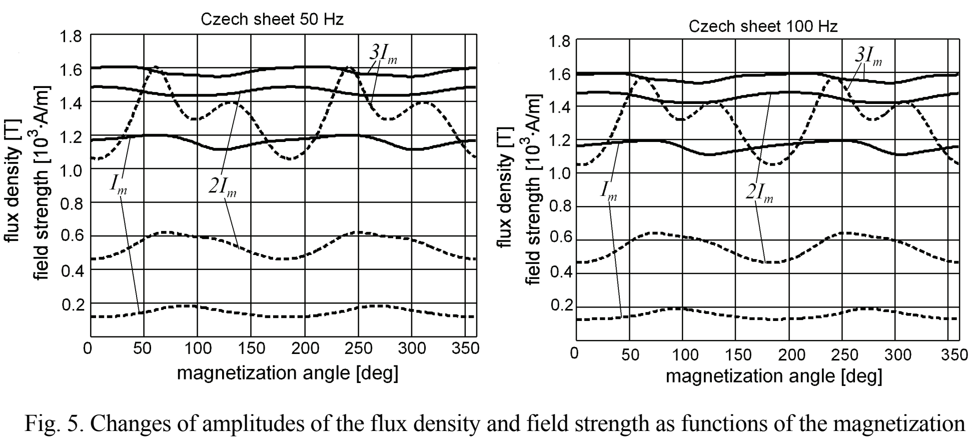

Fig. 5. Changes of amplitudes of the flux density and field strength as functions of the magnetization angle in the Czech dynamo sheet; continuous lines – flux density changes, dotted lines – field strength changes

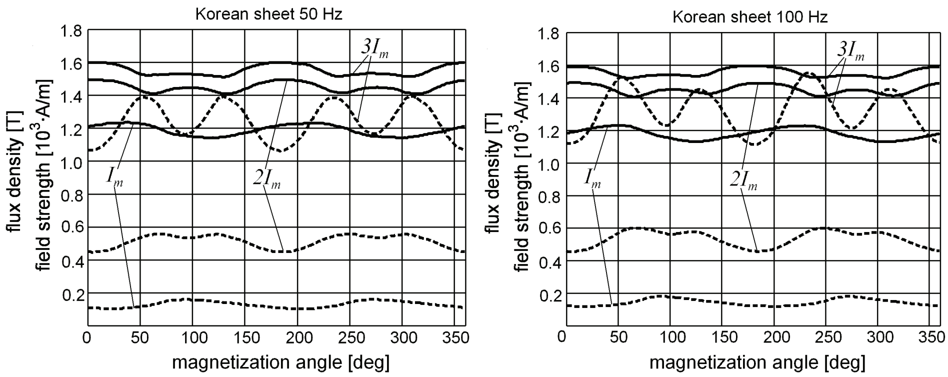

Fig. 6. Changes of amplitudes of the flux density and field strength as functions of the magnetization angle in the Korean dynamo sheet; continuous lines – flux density changes, dotted lines – field strength changes

5. Conclusions

This paper briefly presents the influence of the magnetic anisotropy on magnetization processes in typical dynamo sheets. This anisotropy can cause quite significant differences between magnetization processes which occur in different directions on a dynamo sheet plane. It is understood that these differences depend on the anisotropy degree. Therefore, further studies on a given problem should focus on the assessment of errors in the cases in which the magnetic anisotropy has not been taken into consideration.

Research on the anisotropic properties of dynamo sheets was performed for two types of dynamo sheets. However, in order to obtain meaningful results and to formulate general conclusions, appropriate studies should be carried out for a greater number of typical dynamo sheets produced by different manufacturers.

The magnetic anisotropy was taken into account with the use of the grain distribution function. For simplification of the magnetization model, it was assumed that all iron grains in dynamo sheets have only one easy magnetization axis. However, in reality the cube-shaped iron grains have three easy magnetization axes. Therefore, further studies should also focus on the errors related to this assumption.

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