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SPECIFIC POWER LOSS OF TYPICAL DYNAMO STEEL SHEETS

STRATNOŚĆ TYPOWYCH BLACH PRĄDNICOWYCH

A b s t r a c t

In typical dynamo steel sheets, the magnetization process can have a two-fold character. In parts of the dynamo sheets which refer to the stator core of induction motors the magnetization process has a rotational character. On the other hand, the axial magnetization occurs mainly in the stator teeth. This paper discusses the specific power loss of typical dynamo sheets and its dependence on the magnetization frequency and on the maximum value of the flux density in dynamo sheets. Anisotropic properties of these sheets were taken into consideration. Special attention was given to understanding the dependency of the magnetization direction on specific power loss. The measured specific power losses of two selected dynamo sheets were compared with results obtained on the basis of analytical formulas.

Keywords: *anisotropy*, *dynamo steel sheets*, *specific power loss*

S t r e s z c z e n i e

Proces magnesowania w typowych blachach prądnicowych może mieć dwojaki charakter. W częściach blach, które odnoszą się do rdzenia stojana maszyn indukcyjnych, proces magnesowania ma charakter obrotowy. Natomiast magnesowanie osiowe występuje głównie w zębach stojana. Niniejszy artykuł dotyczy stratności typowych blach prądnicowych oraz ich zależności od częstotliwości przemagnesowania i maksymalnej wartości indukcji występującej w blachach prądnicowych. Specjalną uwagę poświęcono zależności stratności od kierunku magnesowania w płaszczyźnie blachy. Zmierzone wartości stratności dla dwóch wybranych blach prądnicowych zostały porównane z wartościami stratności, które wyznaczono na podstawie wzorów analitycznych.

Słowa kluczowe: *anizotropia*, *blachy prądnicowe*, *stratność*

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1. Introduction

Dynamo steel sheets are mainly used in constructions of stators and rotors of induction and synchronous motors. In stator cores, the magnetization process has mainly an elliptical character, but in stator teeth, axial magnetization occurs very often. When a dynamo sheet has isotropic properties, the power losses in particular stator teeth are the same. However, most dynamo sheets have certain anisotropic properties in terms of both their magnetic properties and power losses. This means that the amount of specific power loss depends on the direction of the magnetic field changes on the sheet plane with respect to the rolling direction in the given dynamo sheet.

It is worth underlining that dynamo steel sheets are quite often used in constructions of cores of small power transformers. For this purpose, the *E* and *U* sheet shapes for transformer cores are cut out from these sheets. Worse magnetic properties in directions other than the rolling direction of dynamo sheets cause decreases in the value of the resultant magnetic flux in the transformer core. Inferior magnetic properties in directions other than the rolling direction of dynamo sheets could lead to decreased values of the resultant magnetic flux in the transformer core.

2. Calculation of the specific power loss in steel sheets

Accurate calculations of power losses in magnetic circuits of electrical machines and transformers continue to be an important research area. It is well known that total power losses are treated as a sum of hysteresis losses, eddy current losses, and excess losses which are caused by the so-called domain eddy currents in electrical steel sheets [1–3]. The reasons for power losses during the axial and rotational magnetization processes are similar, but their calculation varies considerably due to different mechanisms of each process. In practice, losses occurring in steel sheets are given per mass unit and they are referred to as specific power losses. Unlike losses in the rotational magnetization, power losses occurring during the axial magnetization can be estimated by using analytical formulas. The general formula determining the hysteresis specific power loss has the well-known form [4–6]:

$$p_h = \eta \, f \, B_m^x \tag{1}$$

where:

- η – constant whose value depends on the given electrical steel sheets (frequently it is equal to 0.038),
- f – frequency of magnetic field changes,
- B_m – maximum value of the flux density during the magnetization process,
- x – exponent which is equal to 1.6 in the Steinmetz's formula or 2.0 in the Richter's formula [4].

In some cases, concerning the calculation of the specific hysteresis power loss, the following relation is used [6]:

$$p_h = \xi \, f \, B_m^2 \, \frac{1}{kd} \, \frac{shkd - \sin kd}{chkd + \cos kd} \tag{2}$$

where:

ξ – coefficient depending on the given electrical sheet,

d – thickness of the given dynamo sheet,

k – coefficient determined as $k = \sqrt{0.5 \, \omega \, \mu \, \gamma}$,

ω – pulsation $2\pi f$,

μ – magnetic permeability,

γ – conductivity of the given dynamo sheet.

It is worth underlining that hysteresis losses are also calculated with the use of a chosen hysteresis model. An interesting approach concerning the determination of hysteresis losses occurring in induction machines supplied by voltage source inverters is proposed in [7].

The specific power loss of 'classical' eddy currents are usually estimated with the use of the formula [4–6]:

$$p_{ed} = \frac{\gamma \, \pi^2 \, d^2 \, f^2 \, B_m^2}{6} \tag{3}$$

where all parameters are defined in the previous relations.

It should be remembered that the discussed formulas have been formulated assuming a constant value of magnetic permeability. However, for most dynamo sheets, the magnetization characteristic has a curvature when values of flux densities are about 1 T. Due to this, the magnetic permeability does not have a constant value in the whole range of changes of the magnetic flux density. Additionally, in dynamo sheets with the thickness of 0.5 mm or more, the distribution of the magnetic field is not homogeneous when the frequency is equal to 50 Hz or higher. It is necessary to stress that none of the above-mentioned formulas take into account the dependence of power losses on magnetization direction.

Many problems in the estimation of power losses in electrical steel sheets occur during calculations of losses caused by the so-called domain eddy currents. These micro currents appear around the moving domain walls. The model of domain wall motion proposed by Pry and Bean allows us to estimate these losses but only in transformer sheets which usually have an ordered grain structure [8]. However, grains in typical dynamo sheets are arranged randomly. Thus, most of these sheets have certain anisotropic properties [9]. At this point the method worked out by G. Bertotti, who has proposed statistical approach to estimate the eddy current losses [2, 10], should be mentioned. He assumed that the movement of the domain walls during the magnetization process consists of random jumps in the iron crystals of the dynamo sheet. He treated fragments of these walls as certain magnetic objects.

Estimation of power losses during the rotational magnetization is a qualitatively different problem. Determination of these losses is much more difficult than calculations of losses during the axial magnetization. Until now, analytical formulas allowing us to simply estimate power losses under rotational magnetization have not been formulated. These power losses are determined with the use of the basic formula, which is widely presented in [2, 3, 11]. It is necessary to stress that the total power losses occurring in the magnetic circuits of electrical machines are determined with the use of a chosen machine model, where special attention is paid, for example, to calculations of additional losses caused by higher harmonics [12].

3. Dependence of the specific power loss on magnetization direction

Dynamo steel sheets should have isotropic properties. However, different magnetic measurements show that most dynamo sheets have a certain anisotropy, both in terms of the magnetization curves and power losses. These anisotropic features have been confirmed by crystallographic studies on the possible occurrence of textures in dynamo sheets. On the one hand, the magnetization process occurs most easily along the rolling direction in the given sheet; on the other hand, power losses are the biggest when the magnetization process takes place along the transverse direction with respect to the rolling direction. An analysis of the dependence of the specific power loss on the magnetization angle was carried out on the basis of the magnetic measurements, because up until now, formulas which would allow us to calculate the hysteresis and eddy current losses whilst taking into account the magnetization angle have not yet been carried out. Measurements were performed for two selected typical dynamo sheets marked as M530-50A, one of which is produced in the Czech Republic, and the other in South Korea. Figure 1 presents values of the specific power loss in both dynamo sheets as the dependence on the magnetization angle*. Measurements were performed for the following frequencies: 25 Hz; 50 Hz; 75 Hz; 100 Hz. The specific power losses are presented for the flux density values 1.0 T. and 1.5 T (as is usually determined in standards), and they were approximated by means of the second-degree curves.

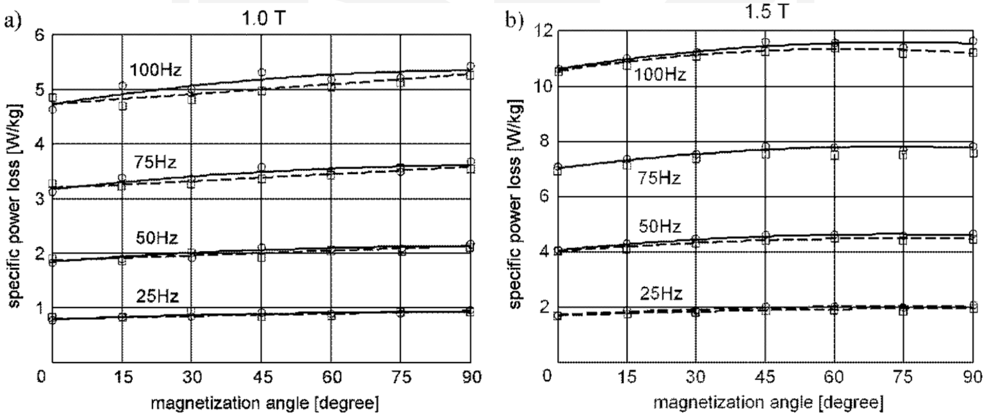

Fig. 1. Specific power loss for Czech and Korean dynamo sheets: a) $B_m = 1.0$ T; b) $B_m = 1.5$ T; continuous lines – Czech dynamo sheet, dashed lines – Korean dynamo sheet, circles and squares denote the measured values of the Czech sheet and the Korean sheet, respectively

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

Higher values of the specific total power loss occur during the magnetization along directions on the sheet plane which significantly differ with respect to the rolling direction. Differences of the specific power losses may be higher than ten percent with respect to the rolling direction. It can be assumed that bigger hysteresis specific power loss in these directions are the direct cause of greater total specific power loss. Figure 2a) presents hysteresis loops of the Czech dynamo sheet for three magnetization directions and for the flux density 1.0 T. In turn, Fig. 2b) shows hysteresis loops when the maximum value of the flux density was equal to 1.5 T; in this case, hysteresis loops measured along the direction of 45 and 90 degrees are almost the same. Due to magnetic anisotropy, hysteresis loops measured along directions inclined 45 or 90 degrees with respect to the rolling direction are wider than hysteresis loops in the rolling direction.

The Korean dynamo sheet has similar properties to the Czech dynamo sheet (Fig. 3).

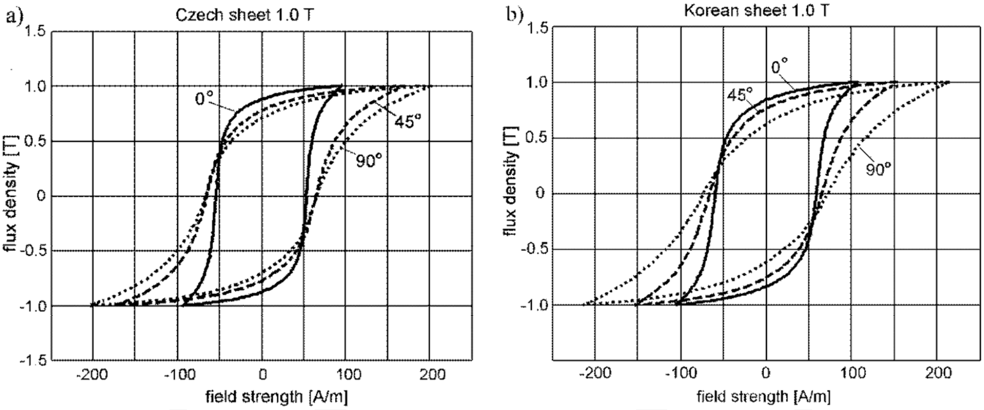

Fig. 2. Hysteresis loops for B_m = 1.0 T: a) Czech sheet, b) Korean sheet

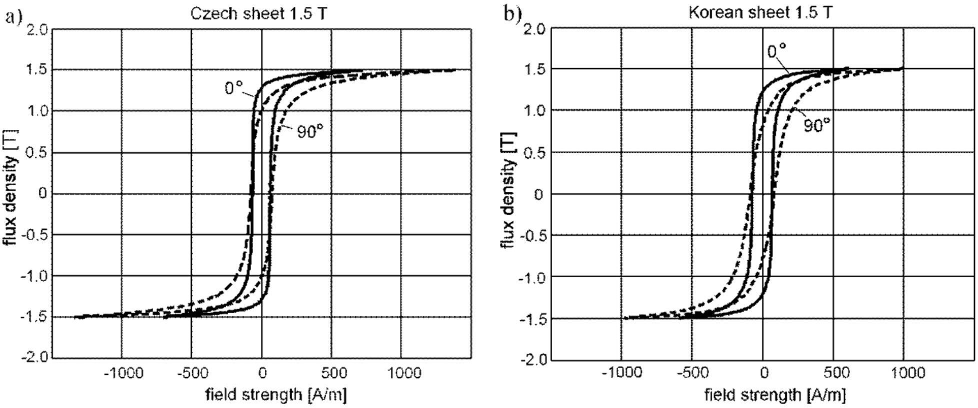

Fig. 3. Hysteresis loops for B_m = 1.5 T: a) Czech sheet, b) Korean sheet

Table 1 presents, by way of example, hysteresis specific power losses for both of the tested dynamo sheets in seven magnetization directions. Hysteresis specific power losses in the transverse direction are about twenty percent higher than specific power losses determined in the rolling direction. Both the magnetic anisotropy and the loss anisotropy are caused by the occurrence of certain textures, this is a characteristic property of most dynamo steel sheets [9]. This means that a certain amount of grains have a privileged crystallographic orientation. It should be noted that the standards define the acceptable anisotropy of power losses in the range 10 to 14%. It is worth noting that losses for directions higher than 45 degrees with respect to the rolling direction are practically the same.

On the basis of magnetic measurements, the losses caused by eddy currents were determined as the differences between measured total power losses and hysteresis losses, wherein the latter were the product of the hysteresis losses per cycle and the magnetization frequency. Measurements performed for two mentioned dynamo sheets, and estimations carried out on the basis of the measured results show that generally, power losses caused by eddy currents do not depend on the direction of the magnetic field changes when values of the flux density are not higher than 1.0 T and the frequency does not exceed 50 Hz. These losses decrease with increases of the magnetization angle for higher frequencies and higher values of the flux density occurring in the given dynamo sheet. Figure 4 presents specific power losses caused by eddy currents as a dependence of the magnetization angle.

Table 1

Hysteresis specific power loss in W/kg

Magnetization angle	Czech sheet		Korean sheet	
	1.0 T	1.5 T	1.0 T	1.5 T
0°	0.025	0.055	0.026	0.055
15°	0.027	0.060	0.026	0.056
30°	0.028	0.062	0.028	0.060
45°	0.030	0.066	0.029	0.063
60°	0.030	0.067	0.030	0.065
75°	0.030	0.067	0.031	0.064
90°	0.031	0.066	0.032	0.065

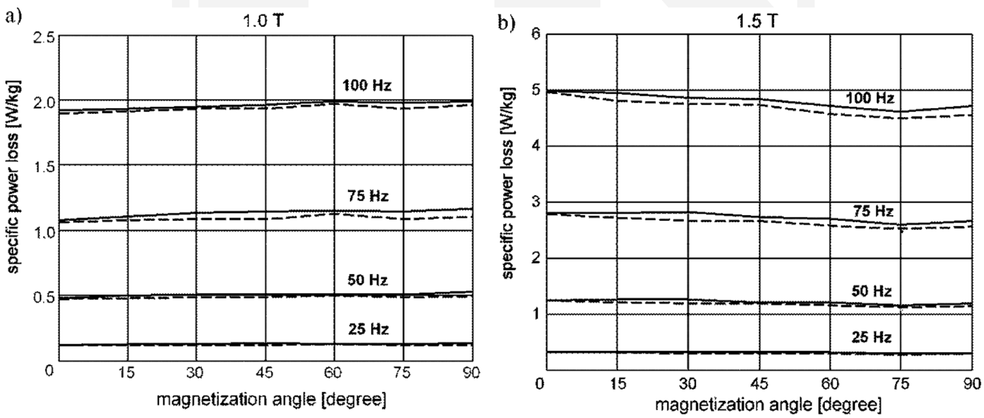

Fig. 4. Specific power loss caused by eddy currents: a) for $B_m = 1.0$ T; b) $B_m = 1.5$ T; continuous lines – Czech dynamo sheet, dashed lines – Korean dynamo sheet

4. Comparison between measured and calculated specific power losses

In many papers, it is concluded that the measured losses are significantly bigger than the calculated losses. As mentioned in Chapter 2, reasons of these differences are the so-called domain micro eddy currents which occur around moving domain walls. However, these remarks refer first of all to the transformer steel sheets. Their grains, and thus their domains, may have an area of several square centimeters. On the other hand, the average size of grains in dynamo sheets is in the range of 60 to 100 μm, and in the majority, grains are arranged randomly. The occurrence of the excess losses in the dynamo sheets is rather a controversial issue. Although

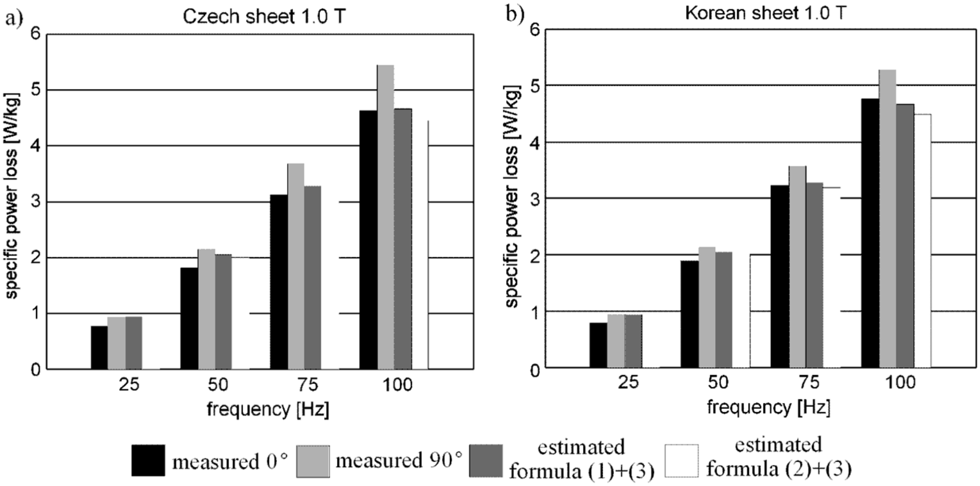

Fig. 5. Measured and calculated specific power loss for B_m = 1.0 T: a) Czech dynamo sheet, b) Korean dynamo sheet

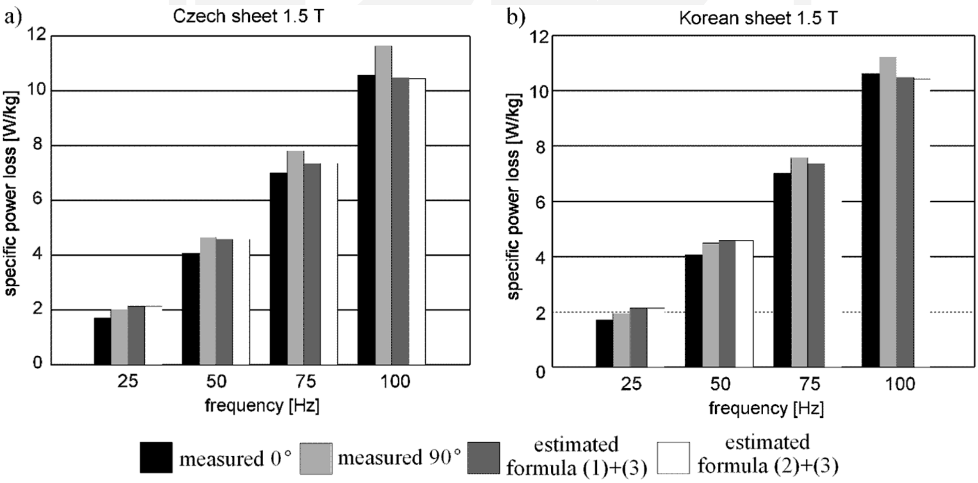

Fig. 6. Measured and calculated specific power loss for B_m = 1.5 T: a) Czech dynamo sheet, b) Korean dynamo sheet

G. Bertotti showed that the measured losses in a certain dynamo sheet are bigger than calculated losses [1], the research carried out for some typical dynamo sheets does not generally confirm this fact. It is obvious that the value of the calculated losses depends on the applied formulas in estimation of the hysteresis and eddy current losses. Figure 5 presents comparisons between the measured losses and the estimated losses during the axial magnetization along the rolling (0°) and transverse direction (90°). The latter losses are calculated for two cases. In the first one, hysteresis losses were estimated with the use of formula (1) (Richter formula) and in the second case, relation (2) was applied. In both cases, eddy current losses are estimated by means of formula (3). Estimated values of power losses depend significantly on coefficients which concern the given soft magnetic material. To reduce the differences between measured and calculated losses, we assumed that the coefficient η in formula (1) and the coefficient ξ in (2) are smaller than is proposed in the literature and they both are equal to 0.035. It should be stressed once again that the above mentioned formulas do not take into account the direction of the magnetization process. The smallest errors between the values of themeasured and estimated losses occur when the power losses are estimated with the use of the sum of formulas (1) and (3). However, these errors amount to 10–20 percent. Similar differences between the losses occur also for the Korean dynamo sheet.

5. Conclusions

Determination of the total specific power loss in typical dynamo sheets with the use analytical formulas without taking into account the magnetization angle can cause errors of even up to 20 percent. Differences in the specific power losses for individual magnetization directions are caused by the presence of anisotropy properties. It may be assumed that this is due to higher hysteresis losses for the magnetization directions other than the rolling direction. However, the formulation of more general conclusions requires studies of a larger number of typical dynamo steel sheets.

Further research should aim at deriving such analytical formulas relating to hysteresis losses that could take into account the magnetization direction. These studies should also include a dependence of eddy current losses on the magnetization angle for frequencies higher than 50 Hz. Specific power losses obtained by means of different analytical relations should also be compared with the values estimated with the use of the general formula. In further research works, attention should be also given to the exceed losses and their dependence on magnetic parameters of dynamo steel sheets.

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