

Effects of Wound Toroidal Core Dimensional and Geometrical Parameters on Measured Magnetic Properties of Electrical Steel

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Abstract: The aim of this paper is to present the results of measurements for the magnetic hysteresis loop and the specific power loss of the electrical steel obtained with the toroidal samples of various dimensions. All samples have been made of the same material. Numerous measurements have been performed after the annealing of the samples. The measurements have been performed with control of the sinusoidal shape of the secondary voltage. Differences between the results of measurements have been analyzed. Change in the measured results, e.g. the shape of the hysteresis loop or the specific power loss has been correlated to the dimensions of the sample.

Keywords: Specific power loss, Hysteresis loop, Toroidal core, Electrical steel.

1 Introduction

Wound toroidal cores made of electrical steel sheet have been widely used in the characterization of this kind of magnetic material. Nevertheless, when it comes to the determination of the magnetic characteristics of these materials, this kind of sample is still not up to standards. This occurs due to evident influence of the sample dimensions in the measurement results, hence different measurement results could be obtained for a variety of dimensions of samples made of the same material. Some specific cases have been analyzed earlier in [1 – 4]. In [1, 2] the authors have concluded that better performances of wound toroidal cores can be achieved by increasing its aspect ratio. Also, better performances may be achieved by increasing the diameters, though this effect is only detected when constant build-up and strip width are employed. General conclusion is that the toroidal cores should be designed using wide strip having a large internal diameter and low build-up. This will lead to the minimization of the effect of normal flux which contributes to the increase in the power loss. In [3] the authors have found that when the ratio of the outer diameter and inner diameter gets larger, the iron loss per unit weight increases. Furthermore, when this ratio is smaller than 1.3 the rate of the increase of the iron loss in

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comparison to the reference is below 1%; the iron core properties become close to the raw-material properties regardless of the magnetizing conditions. Another interesting research has been presented in [4]. The mathematical model for the estimation of the dynamic losses of grain oriented 3% SiFe toroidal wound cores up to 1 kHz, presented in this paper, introduces six constants. Three of these six constants depend on geometrical parameters of the toroidal core. Change of these constants with outer diameter, inner diameter and strip width of toroidal cores has been presented as tabular, without any additional mathematical expression. Another three papers [5 – 7] show the application of the artificial neural networks (ANN) in prediction of the magnetic performances of the toroidal cores. The specific power loss and relative permeability has been predicted using ANN with 3-10% error for toroidal core having various dimensions, under various magnetic induction levels and for frequencies up to several kHz.

The results and discussion presented in [1 – 4] bring several general conclusions, although the stated conditions can not always be achieved in the engineering practice. On the other hand, the principle shown in [5 – 7] does not provide solution which can be easily implemented. Consequently, the authors of this paper have done a new research in order to perform the additional examination of individual effects of the toroidal core dimensions and geometrical parameters on its magnetic properties. The idea is to present more details in the measurement results which will be useful for manufacturers, researchers and educators. Several group of toroidal cores with various dimensions and similar geometrical parameters as in [1, 2] have been made using just one kind of the electrical steel. The results obtained with these cores, already presented in [8, 9], show that there are no such effects as those found in [1, 2] when the tests are performed with unannealed samples. However, it is clear that the magnetic properties of the material have significantly changed due to mechanical stresses in these unannealed samples. After annealing the magnetic characteristics of the material significantly improve, but for cores with different dimensions a deviation between results occurs because heat treatment will create microstructural changes according to the plastic deformation in the material.

The aim of this paper is to present the results of measurements obtained using the toroidal samples with different dimensions after annealing. For that purpose a PC based measurement setup has been used. The measurements have been made with or without control of the sinusoidal shape of the secondary voltage. Construction of the magnetization curve, magnetic hysteresis loop and calculation of the specific power loss has been performed with the measurements taken through the LabVIEW application. The obtained specific power loss curves have been compared to the one given by the manufacturer.

Also, variations in the hysteresis loop have been analyzed. These variations have been correlated to the sample dimensions.

2 Measurement Setup

The laboratory measurement setup, based on PC [10], has been presented in Fig. 1.

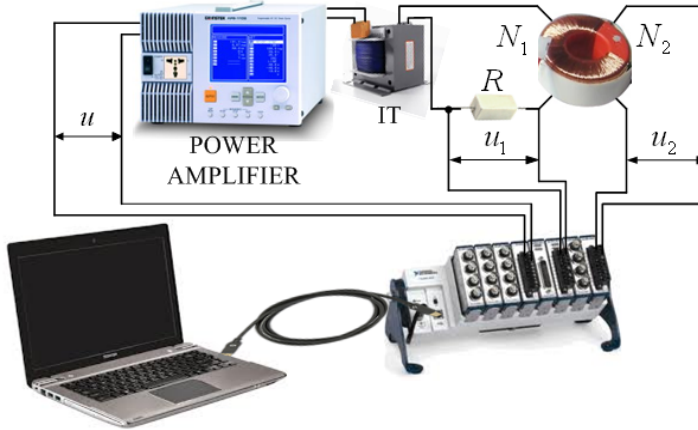


Fig. 1 – Laboratory measurement setup.

A data acquisition card generates the time-varying voltage u . A power amplifier increases this voltage to a desirable amplitude. An insulating transformer (IT) removes the DC component of the amplified voltage. IT secondary voltage creates a magnetization current in the primary winding of the sample N_1 . This current passes through a non-inductive resistor R . The created voltage u_1 is proportional to the magnetization current. The secondary winding N_2 voltage u_2 also occurs. Voltages u_1 and u_2 have been measured by using a data acquisition card. Using these voltages, along with other parameters of the electric and magnetic circuit, the magnetic field strength H , the magnetic induction B and the specific power loss P_s can be calculated as:

$$H = \frac{N_1}{R l_{eff}} u_1(t), \quad (1)$$

$$B = \frac{1}{N_2 S} \int_0^t u_2(t) dt, \quad (2)$$

$$P_s = \frac{f N_1}{N_2 m R} \int_0^T u_1(t) u_2(t) dt, \quad (3)$$

where $l_{eff} = (R_1 + R_2) \pi$, $S = m / (R_1 + R_2) \rho \pi$ and m are the mean magnetic path length, the cross-sectional area and the mass of the magnetic core, while $\rho = 7.65 \text{ g/cm}^3$ is the magnetic material density. R is the resistance of the non-inductive resistor, f is the frequency and T is the period of the electric signals.

During the measurements the secondary voltage can be distorted from the sinusoidal shape. Also, the magnetic induction is distorted in this case. This will cause an increase of specific power loss, and the magnetic hysteresis loop will also be changed. Therefore, to obtain the true magnetic characteristics of the material this distortion must be removed. This can be done using digital feedback control [11]. The measure of purity of the sinusoidal shape of the voltage u_2 is the form factor, which should be $1.111 \pm 1\%$ [12, 13], and distortion which should be below 5%. So the form factor and the distortion of the secondary voltage have been calculated during the measurement.

All measurements and analyses have been performed through an application made in the LabVIEW software. In each measurement, LabVIEW application calculates the magnetic field strength H , the magnetic induction B , the specific power loss P_s , plots the magnetic hysteresis loop, current and voltages waveforms and creates a magnetization curve. All measured and calculated data can be saved in the computer memory.

3 Test Specimens

The geometry of the test specimens and their actual dimensions has been presented in Fig. 2 and **Table 1**.

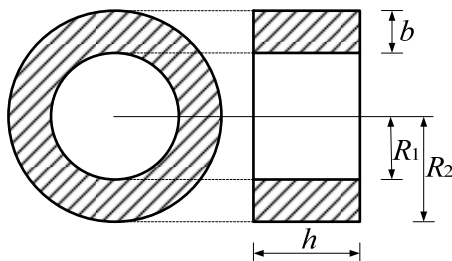


Fig. 2 – Test specimen geometry.

All samples have been made from grain-oriented electrical steel produced by POSCO from South Korea (marked as 27PH100). Core dimensions have been selected as in [1, 2] in order to obtain the desired aspect and winding ratios. The aspect ratio and the winding ratio have been defined as $AR = h/b$ and $WR = R_1/h$, respectively, where h is the strip width and b is the build-up of the toroidal core, Fig. 2. Their values have been also presented in **Table 1**.

The first and second group of the samples can be divided into two subgroups. The first subgroup has constant AR and variable WR (I group – samples 1-6, II group – samples 3-5). For the second subgroup the opposite rule can be applied.

All samples have been annealed in box furnace. Annealing has been performed on the temperature of 820°C during two hours. After that period temperature has been continually decreased with cooling rate of 60°C/h.

Table 1
Toroidal core samples dimensional and geometrical parameters.

Coil	N_1	N_2	R_1 [mm]	R_2 [mm]	h [mm]	m [kg]	AR	WR
I group								
1	85	20	20	24	10	0.043	2.5	2
2	85	20	20	25	10	0.053	2	2
3	85	20	20	30	10	0.118	1	2
4	85	20	20	33	10	0.163	0.77	2
5	85	20	20	36	10	0.211	0.625	2
6	85	20	20	39	10	0.264	0.53	2
7	85	20	20	25	10	0.053	2	2
8	150	20	40	45	10	0.107	2	4
9	200	20	50	55	10	0.125	2	5
II group								
1	120	20	30	37.5	15	0.173	2	2
2	175	20	45	52.5	15	0.241	2	3
3	120	20	30	37.5	15	0.175	2	2
4	120	20	30	40.5	15	0.249	1.43	2
5	120	20	30	45	15	0.391	1	2

4 Results and Discussion

All results presented have been obtained with a variable amplitude AC voltage power supply at a frequency of 50Hz. Some previously obtained results with unannealed samples have showed that there is no significant influence of the toroidal sample dimensions on its measured magnetic properties [8, 9]. New results have been obtained with these samples after annealing. The results from the previous and new measurements show the improvement in the magnetic characteristics of the material after annealing. For example, the peak value of the magnetic induction for unannealed samples, when a 1000 A/m magnetization field has been applied, was about 1.1 T. In the same conditions with annealed samples, this value was about 1.9 T. Similarly, the specific power loss has changed significantly. For a magnetic induction of 1.1 T with the unannealed samples the loss amounted to 1.0 W/kg. After annealing this was reduced to about 0.5 W/kg.

Digital feedback control has been used to maintain the secondary voltage sinusoidal during the measurements. Results in Fig. 3 show a slight difference between the specific power loss curves for both controlled and uncontrolled magnetization. The results for the samples from the first group, Fig. 3, show that controlled magnetization produces a little less power loss (for some samples this difference has not been found). Even so, all further results presented have been obtained with controlled magnetization.

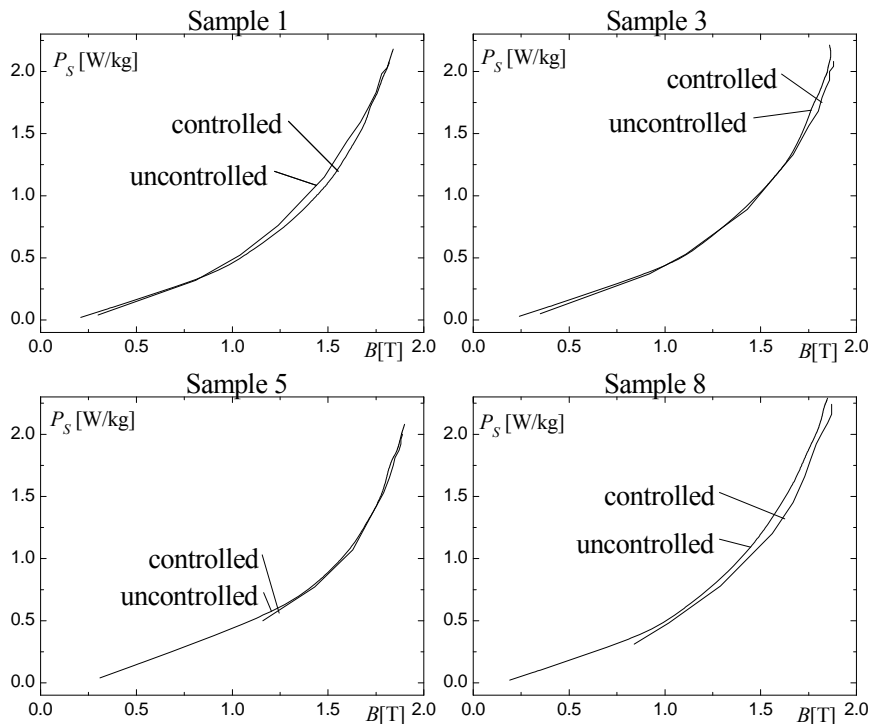


Fig. 3 – Specific power loss under controlled and uncontrolled magnetization.

On the contrary, a significant difference has been noticed in the results obtained for most of the samples from the first and second group after annealing. Before annealing, only a slight difference between results has been noticed [8, 9]. This small difference (several percents) has been evidenced in the specific power loss for the samples from the first and second group. The conclusion was that the larger strip width causes smaller power loss when cores are in deep saturation. After annealing the differences are much grater. For example, for the samples with constant WR from the first group the obtained specific power loss curves are significantly different, Fig. 4. This group of samples has a constant inner diameter and strip width but a variable outer diameter.

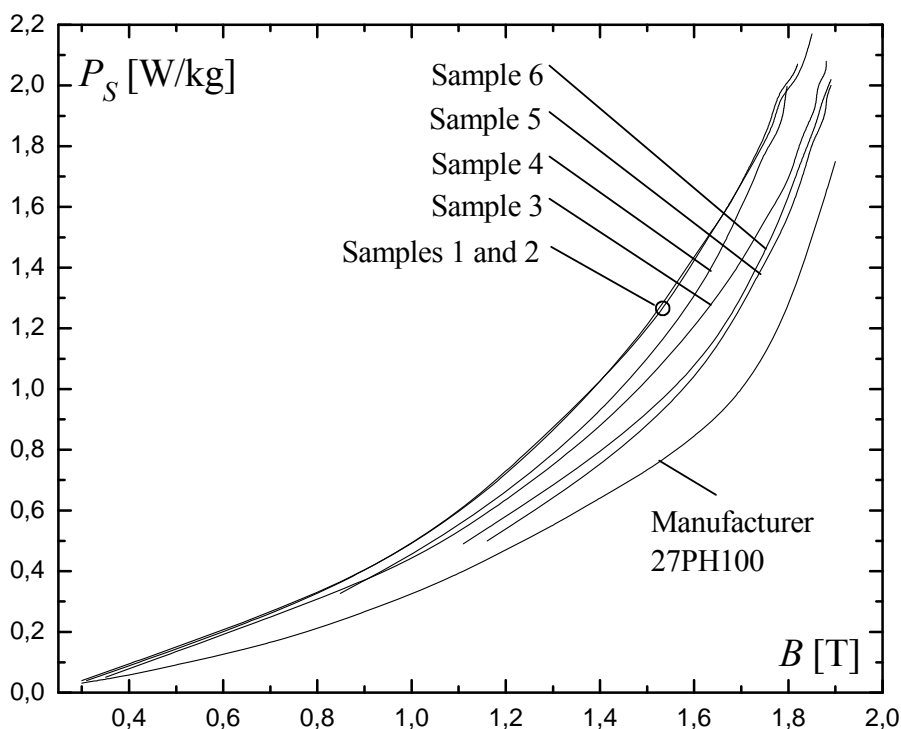


Fig. 4 – Specific power loss variation (I group).

It is evident that samples 1 and 2 give practically the same result. Samples 3 and 4 produce less specific power loss than samples 1 and 2. Also, the difference among these two samples is evident for higher magnetic induction. Curves obtained for samples 5 and 6 show even lower specific power loss. The difference between these two curves is smaller than for samples 3 and 4. All curves obtained give a higher specific power loss than that given by the manufacturer (obtained with Epstein frame). The variation in the measured specific power loss from that given by the manufacturer for the induction of 1.7 T (amounts to 0.98 W/kg), is given in **Table 2**. The reason for this high difference is connected with dimensions of the toroidal core. For core with small inner and outer diameter high loss can be expected [2]. During the tape winding process high mechanical stress occurs in the material. Stress relief annealing may cause significant microstructural changes in the material, which reflects in the power loss increase. For the samples with small inner diameter another significant phenomenon occurs. In an ideal solid toroidal core the flux flows entirely in a circumferential direction. However, in a wound toroidal core the strip is wound as a spiral, so the flux needs to cross the small air gaps to complete the magnetic circuit. The flux transferred from one layer to another

has a normal component which produces extra power loss [2]. This phenomenon is more prominent in the cores with small diameters and build-up, like samples 1 and 2 in this case. For samples with small inner diameter and larger outer diameter (bigger build-up) this effect has not been investigated in [2]. According to the results shown in **Table 2**, samples 3-6 from this group have smaller power loss than samples 1 and 2, but the variation in the results can be noticed. This variation can be caused by a combination of the individual effects, such as: microstructural changes in the material, normal flux, high variation in the magnetic field strength and magnetic induction inside toroidal core due to large difference between inner and outer diameter, effect of cutting edge, etc.. All these effects depend on the core dimensions, but their individual evaluation is very complicated. It can be concluded that the cores with large build-up should not be used in practice as a part of the final product or as a test sample. In addition, the cores with small inner diameter should be avoided since they produce higher power loss. Standard recommendations are that the ratio of the outer to inner diameter should not be higher than 1.4, and preferably less than 1.25 [13]. This is the case for samples 1 and 2, but samples 5 and 6 have much greater diameter ratio of 1.8 and 1.95 respectively.

Table 2
Specific power loss at 1.7 T.

Coil	P_s [W/kg]	δP_s [%]
1	1.68	71.43
2	1.68	71.43
3	1.42	44.90
4	1.60	63.26
5	1.27	29.59
6	1.30	32.65

The hysteresis loops for this group of samples have been presented in Fig. 5. These loops have been obtained at a magnetization field which amounted to 300 A/m. The difference between the loops is evident. Along with samples 1 and 2, samples 5 and 6 have a very small variation in their loops. At the same time, samples 1 and 2 have the lowest peak magnetic induction and hysteresis loop area at this magnetization field, while the peak magnetic induction of samples 5 and 6 is much greater. Consequently the area of the hysteresis loop becomes larger. Also, the hysteresis loop knee is much more expressed for samples 5 and 6 than for the other samples, so a lower AR with constant WR will give a higher magnetic induction peak and greater hysteresis loop area (specific power loss) at a constant magnetization field.

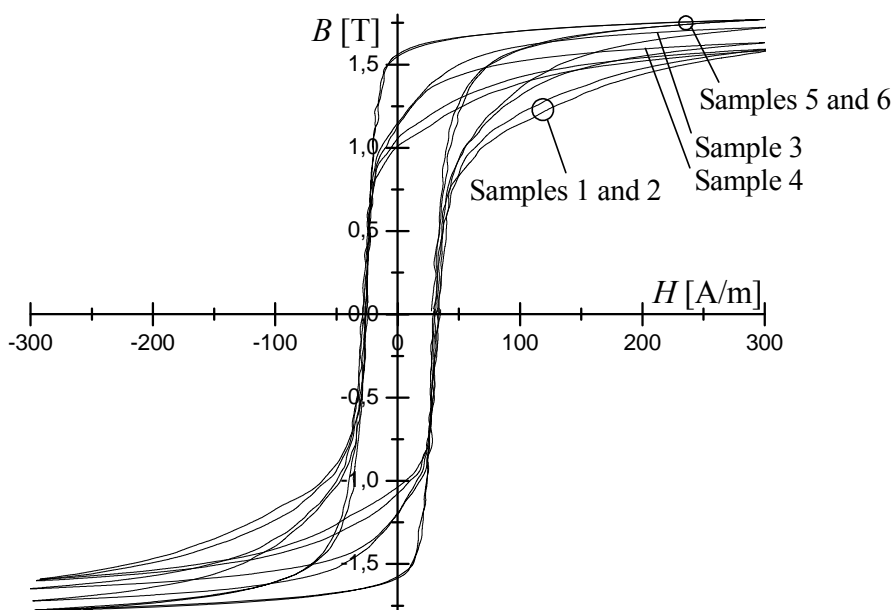


Fig. 5 – *Hysteresis loop variation (I group).*

Like the previous analysis, the results for the specific power loss for samples with constant WR from the second group are presented in Fig. 6. This group has a larger strip width than the previous group but the same WR . Also, the inner diameter of these cores is larger than for those in the first group. In comparison with Fig. 4, the results from Fig. 6 show that these samples cause a lower specific power loss than the samples from the first group and the variation between results is much smaller. Still, these results are higher than those given by the manufacturer by a figure amounting to over 30%. By applying the analysis similar to the first group, we can conclude that the toroidal core with larger inner diameter will cause lower power loss. The reason for this is lower stress during the core producing which causes smaller microstructural changes in the material and thus lower changes in the power loss. The core build-up is much smaller in this group and therefore the variation between the results is not high.

The hysteresis loops for this group of samples have been presented in Fig. 7. These loops have been also obtained at a magnetization field which amounted to 300 A/m. The difference between the loops is evident, but it is much less than for the samples from the first group. Sample 3 has the lowest peak magnetic induction and hysteresis loop area at this magnetization field. Also, the hysteresis loop knee is less expressed for sample 3 than for the other two samples.

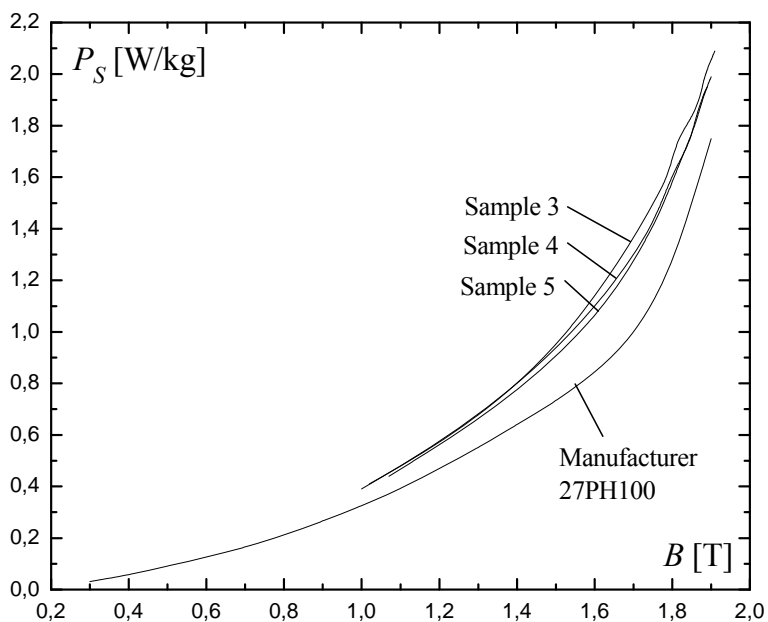


Fig. 6 – Specific power loss variation (II group).

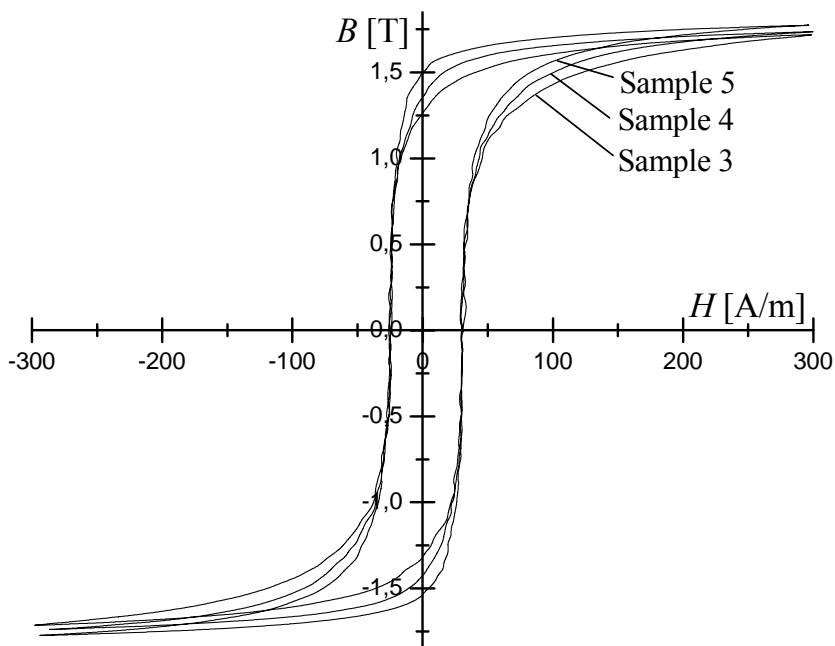


Fig. 7 – Hysteresis loop variation (II group).

Fig. 8 presents the results for the specific power loss for samples with constant AR from both groups. These samples have the same strip width and core build-up, but different inner and outer diameters. All samples have a diameter ratio which is lower or equal to 1.25. It can be seen that the variation between results for samples from the same group is not large, therefore, the variation of the WR does not influence much the results measured (with a note that this group of samples is not a larger enough, and that $AR = 2$ and WR is larger than 2). Also, the obtained results are higher than those given by the manufacturer, by about 38% for the second group and above 60% for the first group.

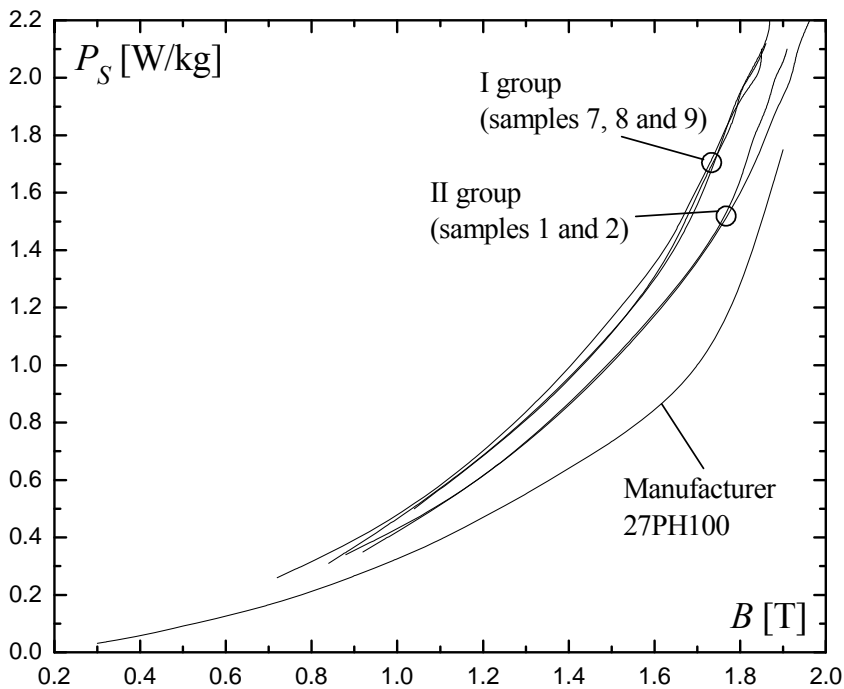


Fig. 8 – Specific power loss variation (I and II group).

5 Conclusion

This paper presents experimental results for the magnetic hysteresis loops and specific power loss in the grain-oriented electrical steel. Measurements have been performed with two groups of samples with different dimensions in order to analyze the effects of the toroidal core dimensions on the measured magnetic characteristics of the electrical steel.

It has been shown that these effects were not significant before annealing of the samples. After annealing, significant differences in the measurement results for most of the samples have been noticed. The obtained specific power loss for all samples is higher than that given by the manufacturer by between 30% and 70%. It has been evidenced that the samples with smaller inner and outer diameter have high power loss. Also, the samples made of strip having smaller width have high power loss. An increase in the toroidal core outer diameter, while the inner diameter and strip width are small, gives slight improvement in the power loss. On the other hand, the variations in the power loss are significant. So, this combination of the dimensional parameters provides inconsistent magnetic properties which are hard to predict. With an increase in the strip width the differences between the results decrease and more consistent magnetic properties have been obtained.

It can be concluded that better magnetic properties of the electrical steel wound in the toroidal core will be obtained if the toroidal core diameters are large, while the core build-up is small. Furthermore, larger strip width will provide more consistent magnetic properties.

6 Acknowledgment

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