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Magnetic properties of amorphous materials used as corps of electric machines

***Abstract**. In the paper the various methods of determining of the magnetization and losses density characteristics as a function of a flux density of the amorphous steel METGLAS Alloy 2605SA1, are presented in a wide range of frequencies. These characteristics will be used in the design calculations of the high-speed induction motors.*

***Streszczenie.** W artykule przedstawiono charakterystyki magnesowania i stratności w funkcji indukcji magnetycznej i częstotliwości blachy amorficznej Alloy 2605SA1 firmy METGLAS, wyznaczone dla próbek pierścieniowych wykonanych z użyciem różnej technologii oraz dla powszechnie stosowanej w pomiarach przy użyciu aparatu Epsteina próbki ramowej. Omówiono możliwości aproksymacji otrzymanych charakterystyk zależnościami analitycznymi w celu wykorzystania pomierzonych wartości w obliczeniach strat w rdzeniu silnika indukcyjnego. (**Właściwości magnetyczne materiałów amorficznych używanych do produkcji maszyn elektrycznych**)*

Keywords: the magnetization and losses density characteristics, measurement methods, amorphous material
Słowa kluczowe: charakterystyki magnesowania i stratności, metody pomiarowe, materiały amorficzne

Introduction

Magnetic materials currently play major role in many fields of science and technology. They are used for the construction of magnetic circuits in many electric devices such as electric machines, chokes and transformers.

The soft magnetic materials find particular application. They can be characterized among other things by narrow hysteresis loop. They are used in magnetic cores of electric machines and transformers [4]. The materials applied in the construction of magnetic cores should be characterized by:

- large saturation induction
- large magnetizability (large magnetic induction occurs at low intensity of the magnetic field)
- narrow hysteresis loop
- large resistivity

Silicon steels, amorphous materials and nanocrystalline materials meet these specifications to a certain degree. Due to its magnetic properties amorphous and nanocrystalline materials are used more often in wide spectrum of applications.

The amorphous materials are obtained by rapid cooling of molten metals. This results in chemical and topological disordered state. These materials are characterized by high resistivity, which is even repeatedly higher than in metals (silicon steel sheet ρ = 45·10-8Ω·m, amorphous strips ρ = 130·10-8Ω·m), large saturation induction B (0,8 ÷ 1,8T), coercive force at the level of Hc = (0,3 ÷ 5) A/m and low value of loss. [5].

The nanocrystalline alloys are obtained by heat treatment of amorphous materials above the crystallization temperature. These alloys are characterized by low loss, saturation induction B at the level 1,2 ÷ 1,7 T, very narrow hysteresis loop, high relative permeability μ=10000÷1500000, low coercive force (<3A/m) and resistivity ρ =110·10-8Ω·m.

They are produced in the shape of stripes (thickness ~25μm). These materials are characterized by very good magnetic properties, yet the drawback is their brittleness which makes mechanical working difficult. While producing magnetic cores one cannot use classic punching operations. In order to get desirable shape of magnetic cores laser beam cutting or water jet cutter of amorphous materials is applied. Both methods have advantages, yet some disadvantages are also present.

Laser cutting causes local overheating of material and this changes its structure and properties. It also results in local short-circuits between layers. In effect, the eddy-current loss increases.

While designing magnetic cores in the electric machines one needs frequency-varying characteristics of magnetization and specific core losses.

Amorphous steel characteristics measurements

In order to get magnetic properties of amorphous material Alloy 265SA1 made by METGLAS (thickness 0,0254mm), which was used in magnetic core designing of high-speed induction motors, the research towards determining magnetization and specific core losses characteristics were conducted. The studies were made for 50 ÷ 350 Hz frequency range at the highest possible values of magnetic flux density [7].

During amorphous materials specimen tests the problem of choosing measurement methods and sample type arises. Making a decision is difficult due to the lack of proper regulations and standards in this field. The authors took into consideration that results of measurements would be applied in designing magnetic cores of induction motors. Therefore, the chosen kind of samples corresponds to the structure which is similar to a magnetic circuit of an electric machine.

In order to determine the influence of given sample type on the magnetization and specific core losses characteristics two ring-shaped and one frame-shaped (to Epstein apparatus) samples were took. The ring-shaped samples used for measurements do not allow determining so-called material characteristics. The obtained results formulate circuit characteristics.

The measurements were carried out using the ring-shaped samples. The first one was made of discs that were cut from amorphous material using spark erosion. The second one was rolled using shears-cut amorphous strip. The dimensions of ring-shaped samples (made of discs) were as follows: outer diameter 120mm, inner diameter 90mm, sheet pack thickness 10,1 mm, mass m_1=325 g.

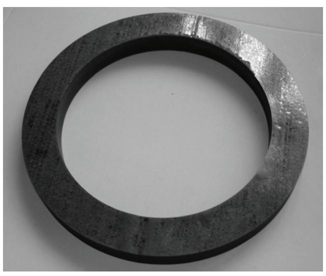

Fig.1. The package consists of amorphous material rings.

After covering the ring-shaped samples with isolation, two windings were made – magnetizing and measuring one. The first one was made using several or tens of coils of the thin wire and was placed closest to the core. The winding should cover minimum possible flux, which leaves ferromagnetic core. Yet the induced electromotive force should not exceed measuring capacity of devices.

The magnetizing winding was wound by using the thick wire on the top, with one coil close to the other using one or more layers.

For the ring-shaped sample made of discs the magnetizing winding consisted of z_1=126 turns and the measuring one of z_2=7 turns.

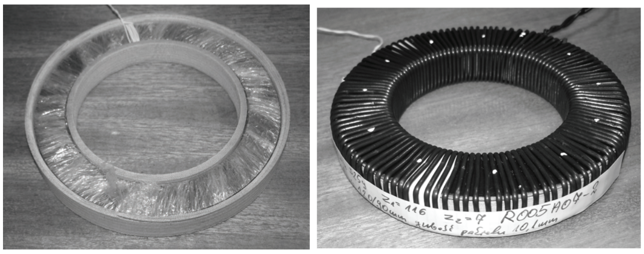

Fig.2. Toroidal core with the measuring and magnetizing winding.

The ring-shaped sample made of amorphous strip had outer diameter 86mm, inner diameter 70mm, height 10 mm, mass m2=128 g. The magnetizing winding consisted of 87 turns and the measuring winding had 12 turns times two.

Moreover, the frame sample weighting 844,1g was also examined. It was made of 576 strips with dimensions 30x280mm adapted for Epstein apparatus. All the three samples were not submitted to stress relief annealing. The magnetic properties research of the frame sample were carried out in accordance with PN-EN-60404-2 standard [6]. The scheme of measuring circuit was presented in the Fig.3.

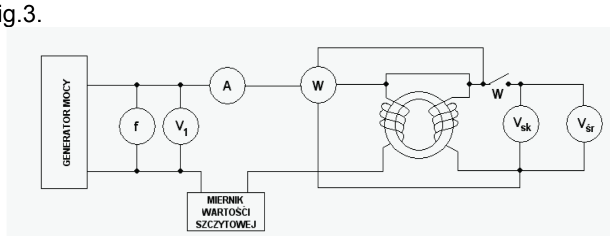

Fig.3. Scheme of the measurement system to study the magnetic properties of samples [2].

The significant part of measuring system is electronic generator - the source of power supply. It enables the voltage and frequency control of the given signal. The measurements of power, magnetizing current, voltage and frequency were carried out with the assistance of Norma 4000 analyser (FLUKE Corp.) [3].

The results of measurements

The results of magnetization characteristics measurements for the ring-shaped sample made of discs, for roll ring-shaped sample and for frame sample in the Epstein apparatus are depicted in Fig. 4. They were evaluated for 50 up to 350 Hz (the characteristics overlap).

As may be observed in the Fig.4 the highest values of magnetic flux density at given value of intensity of the magnetic field are obtained for the frame sample. The worst magnetization characterizes the ring-shaped sample made of discs. Moreover, it was found that the magnetization characteristics do not depend on the frequency of supply voltage. The frequency influences only the width of hysteresis loop.

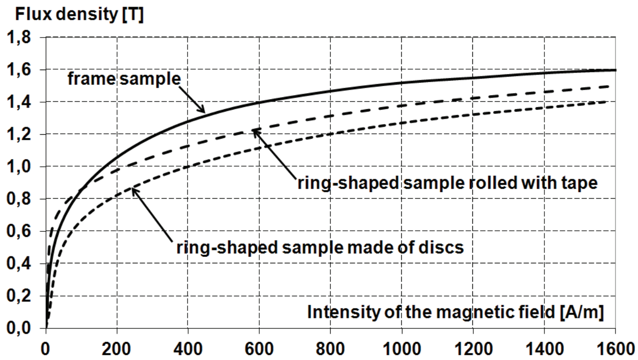

Fig.4. Magnetization characteristics of the ring-shaped sample made of discs, the ring-shaped sample rolled with tape and the frame sample for a 50 -350 Hz frequency range.

The obtained results of measurements of the specific core losses characteristics as a function of magnetic flux density for different frequencies, for different samples are presented in the Fig.5-7.

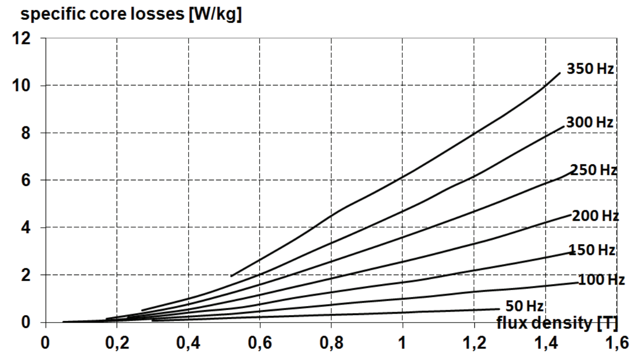

Fig.5. Specific core losses characteristics as a function of peak magnetic flux density of the ring-shaped sample made of discs for a 50 -350 Hz frequency range

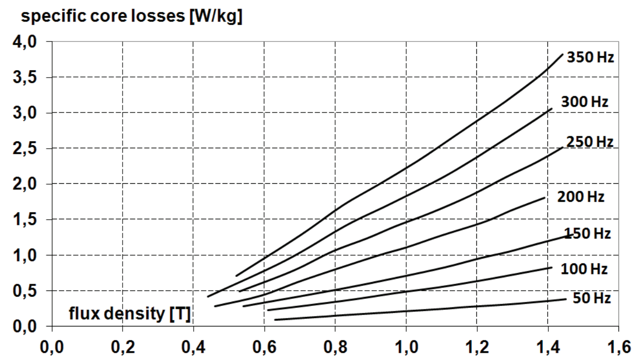

Fig.6 Specific core losses characteristics as a function of peak magnetic flux density of the rolled ring-shaped sample for a 50 -350 Hz frequency range.

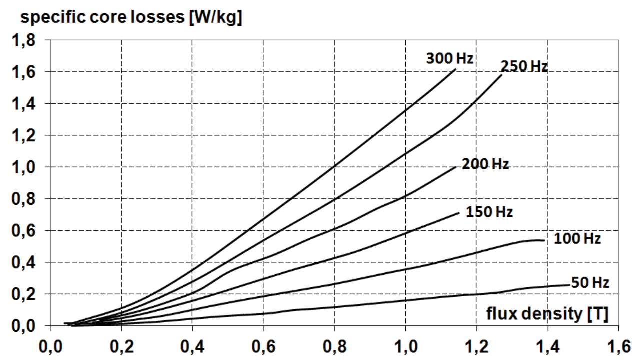

Fig.7 Specific core losses characteristics as a function of peak magnetic flux density of the frame sample for a frequency 50-350 Hz.

Comparing the measurements of the specific core losses for different kind of samples one may observe that the highest specific core losses are present for the ring-shaped sample made of discs. The lowest specific core losses values are observed for the frame sample in the Epstein apparatus. It may be explained by the presence of short-circuits between particular discs. They are the effect of the spark erosion cutting that may cause corrosion. The roll ring-shaped sample was not processed. It results in lower values of specific core losses comparing to the sample which was made of discs. The higher values of specific core losses measured for the roll sample (than in the Epstein apparatus) may have their origin in stresses observed during the rolling the strips in the disc. The characteristics obtained from Epstein apparatus are the ones, which match the catalogue data most.

The specific core losses characteristics for two ring-shaped samples as a function of frequency (in the range up to 2000 Hz) for the different magnetic flux density values are presented in Fig. 8-10

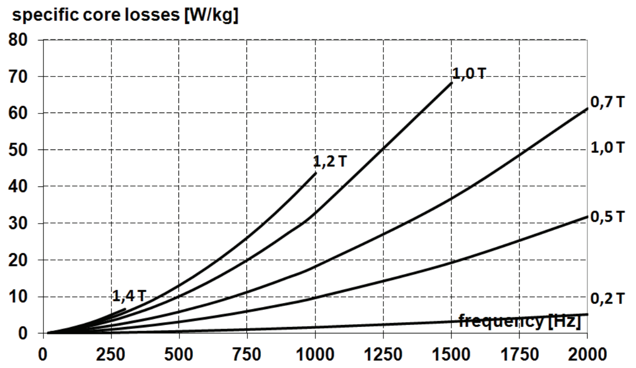

Fig.8 Specific core losses characteristics as a function of frequency of the ring-shaped sample made of discs for a different magnetic flux density values.

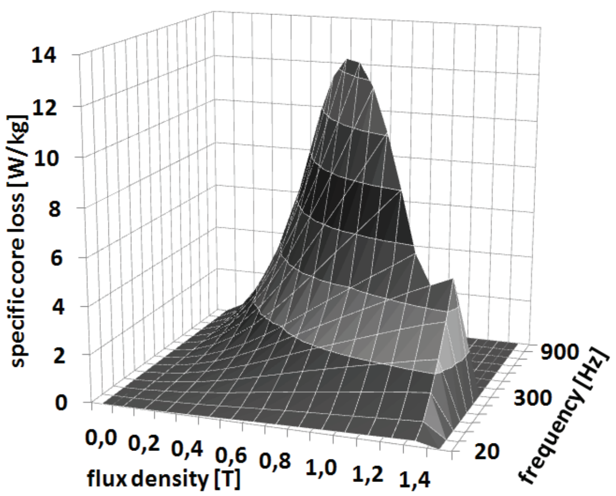

Fig.9 The measured specific core losses characteristic as a function of frequency and magnetic flux density of the ring-shaped sample made of discs [1].

The comparison of the measured specific core losses characteristics as a function of magnetic flux density for different samples for values of frequency 50 Hz and 300 Hz are presented in Fig. 11-12.

The measured and approximated specific core losses characteristics as a function of frequency and magnetic flux density for ring-shaped sample made of discs are presented in Fig. 13.

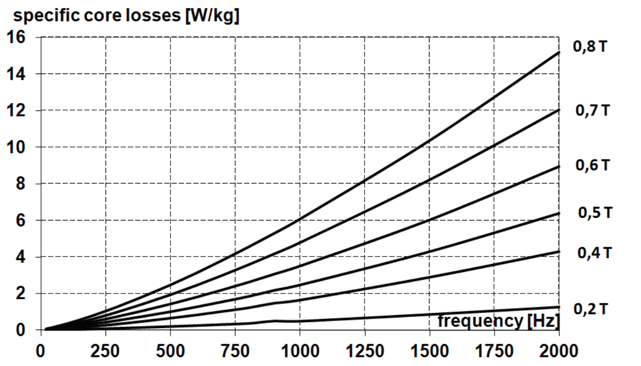

Fig.10 Specific core losses characteristics as a function of frequency of the rolled ring-shaped sample for a different magnetic flux density values

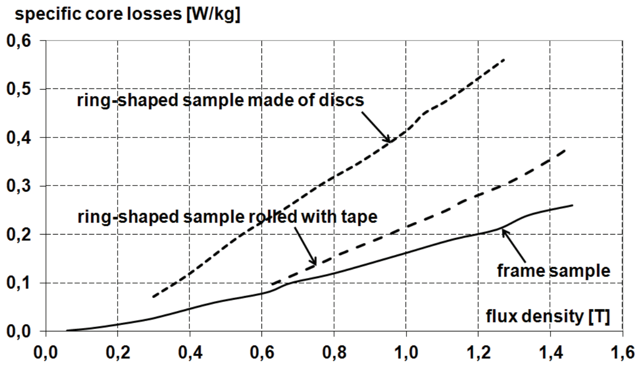

Fig.11 Specific core losses characteristics as a function of magnetic flux density for different samples for value of frequency 50 Hz

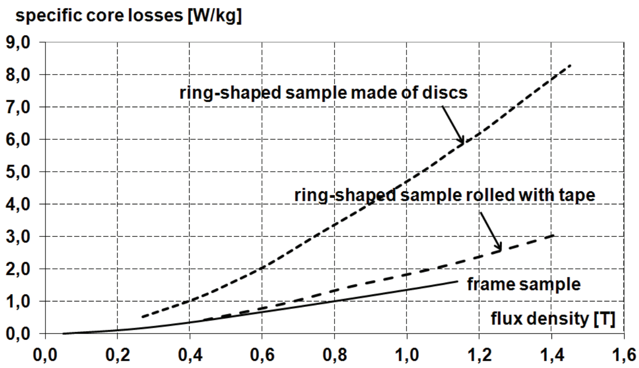

Fig.12 Specific core losses characteristics as a function of magnetic flux density for different samples for value of frequency 300 Hz

These characteristics allow to introduce the analytical relationships describing the specific core losses for the given material: $p=F(B)_{f=const}$ and $p=F(f)_{B=const}$.
The most accurate results can be obtained using 3rd order polynomial approximation of these characteristics (as a function of magnetic flux density and frequency).

In order to determine the specific core loss value of the material for desired value of magnetic flux density and frequency (in the range from 20 to 200 Hz) one can use specific core loss characteristics $p=F(B)_{f=50Hz}$. It was obtained for the ring-shaped sample made of discs and it can be approximated to the different values of frequency in accordance with:

(1) $$p_{B,f} = p_{B,50}\left(\frac{f}{50}\right)^{1,26}$$

The measured and approximated specific core losses characteristics as a function of frequency (for different values of magnetic flux density) for ring-shaped sample made of discs are presented in Fig. 13.

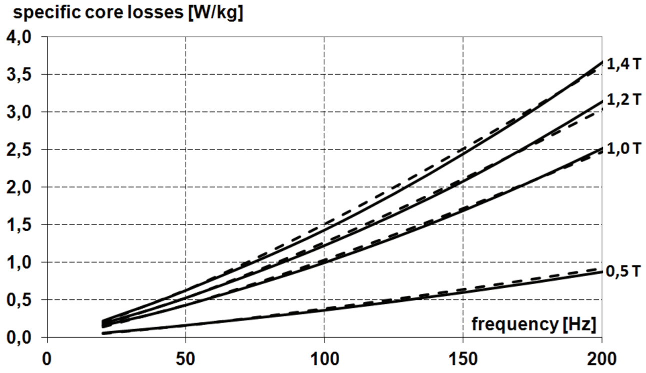

Fig.13. Measured (solid line) and approximated (dashed line) specific core losses as a function frequency for different magnetic flux density of the ring-shaped sample made of discs.

In case of the rolled ring sample the approximated relationship is as follows:

$$p_{B,f} = p_{B,50}\left(\frac{f}{50}\right)^{1{,}17} \tag{2}$$

The measured and approximated relationships (2) of specific core losses characteristics as a function of frequency for the rolled ring-shaped sample (for the different magnetic flux density) are plotted in Fig. 14.

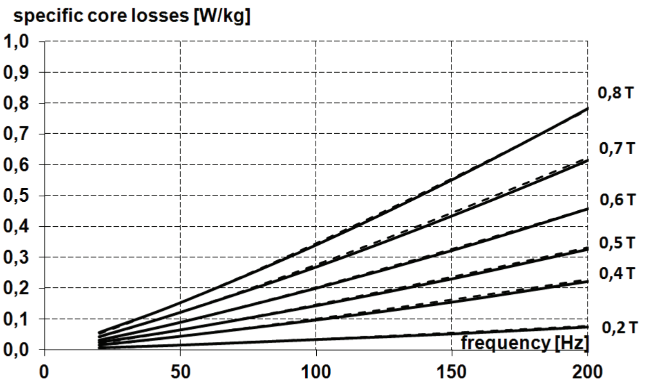

Fig. 14. Measured (solid line) and approximated (dashed line) specific core losses as a function frequency for different magnetic flux density of the rolled ring-shaped sample.

As may be observed in the presented plots the introduced analytical relationships are consistent with the measured values up to 200 Hz frequency. For the higher frequencies, the exponent rises due to the growth of eddy-current loss.

Conclusions

Analysing the magnetization and specific core losses characteristics it can be concluded that these characteristics depend on the type of samples chosen for laboratory tests. On the results also have a significant influence the technology of production the ring and framework samples. Wrong positioning belts of the material creates air gaps, but too tightly too tight winded of coil induce stress in the sample material, which also gives the change of magnetic characteristics of the sample. The exponent in the introduced analytical relationships which approximate the measurement results (up to 200 Hz) concerns the given amorphous material. This exponent also depends on how to do of ring-shape sample. Therefore, in the total loss analysis in magnetic cores the best solution is to use the specific core losses characteristics measured for appropriate magnetic flux density and frequency value and approximated with 3rd order polynomial.

The results most similar to the catalogue data are obtained by testing frame samples in the Epstein apparatus. However, it should be assumed that the characteristics obtained for ring-shaped samples made of discs are the most similar to the characteristics of an induction machine magnetic circuit.

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