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Analysis of magnetic losses in Fe-polymer composites

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The most important properties of soft magnetic materials are peak induction and magnetic losses, determining the size and efficiency of electric devices. Conventional soft magnetic materials are not suitable for the construction of miniaturized magnetic cores. Soft magnetic composites meet miniaturization requirements of electric and electronic devices. In this paper, magnetic losses in self-developed Fe-polymer composites are analyzed. The frequency dependencies of magnetic losses are measured at different level of maximum induction. The influence of Fe-grain size on magnetic losses is also discussed.

Keywords: Fe-polymer composites, Fe-grain size, magnetic losses

1 Introduction

Nowadays, electric and electronic devices are designed to meet the requirements of energy efficiency as well as miniaturization of electric units. However, conventional soft magnetic materials such as electrical steels are not suitable for the construction of miniaturized magnetic cores. For this reason, a new type of core materials – magnetic composites – is becoming increasingly popular. Composites are produced from magnetic powder and dielectric binder. Their magnetic and mechanical properties strongly depend on chemical composition, grain size of magnetic powder as well as technology parameters such as pressure and curing temperature [1-6]. In the case of fine powders, there is a large number of air gaps inside the composite that results in their lower density and worse magnetic properties. Large, sharp-edged grains are better bonded to the dielectric matrix and a number of air gaps inside the material is reduced that improves magnetic properties of the composite [1,3,6].

The most popular and commercially used soft magnetic composites are made from Somaloy powder and organic lubricant Kenolube.

However, other types of Fe-based magnetic composite are also available. For practical applications, the most important properties of magnetic composites are peak induction and magnetic losses, determining the size and efficiency of electric devices. For this reason, magnetic losses in the self-developed Fe-polymer magnetic composites are analysed as well as the influence of Fe-grain size on these losses is discussed in this paper.

2 Samples and the measuring system

Samples of Fe-polymer composite were made of the mixture of pure iron powder (99.5% wt) and polyvinyl chloride (0.5% wt), which insulated and bonded iron powder. Iron powder was prepared in three granules of regular shaped grains with size < 50 μm, 50 to 100 μm and 100 to 150 μm. The samples were formed in a cylindrical shape under a compacting pressure of 507 MPa and a curing temperature of 165 °C. The manufacturing technology of the Fe-polymer samples is described in detail in [7]. All samples have the same dimensions, but the density is different for each of them and it is equal to $7004\,\mathrm{kg/m^3}$, $7122\,\mathrm{kg/m^3}$ and $7147\,\mathrm{kg/m^3}$ for powder grain 50 μm, 50 to 100 μm and 100 to 150 μm, respectively.

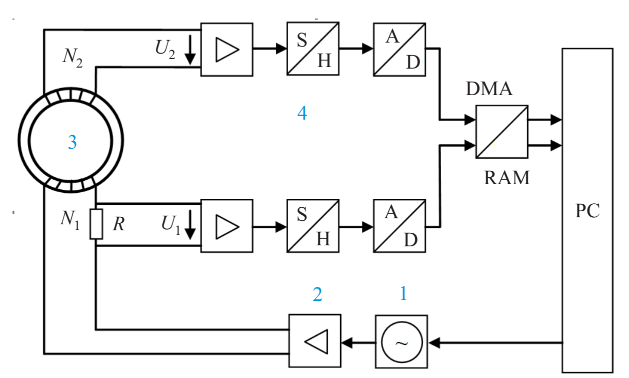

Fig. 1. The REMACOMP® C-200 system: 1 - programmable signal generator, 2 - power amplifier, 3 - specimen, 4 - digital sampling system with preamplifiers and analog/digital converters, $N_{1,2}$ - primary and secondary windings [9,10]

The international standards IEC 60404 [8] recommends the wattmeter method with the Epstein test frame or toroidal sample as the basic measurement method of specific magnetic losses P. These losses can be also measured using other methods, such as the hysteresisgraph or calorimetric methods as well as the unbalanced bridge method [9,10].

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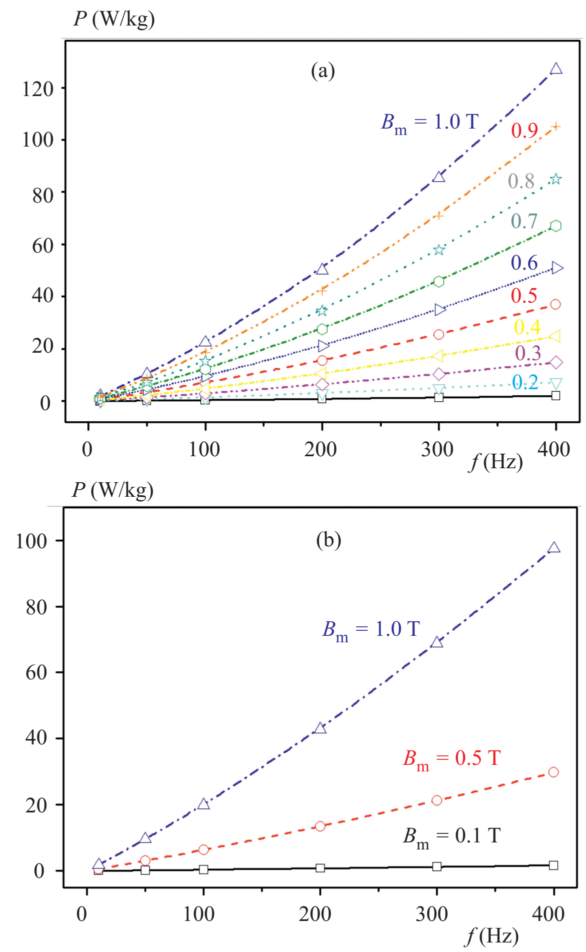

Fig. 2. Frequency dependencies of magnetic losses in Fe-polymer composites: (a) – grain size 50 μm, (b)– grain size 100-150 μm

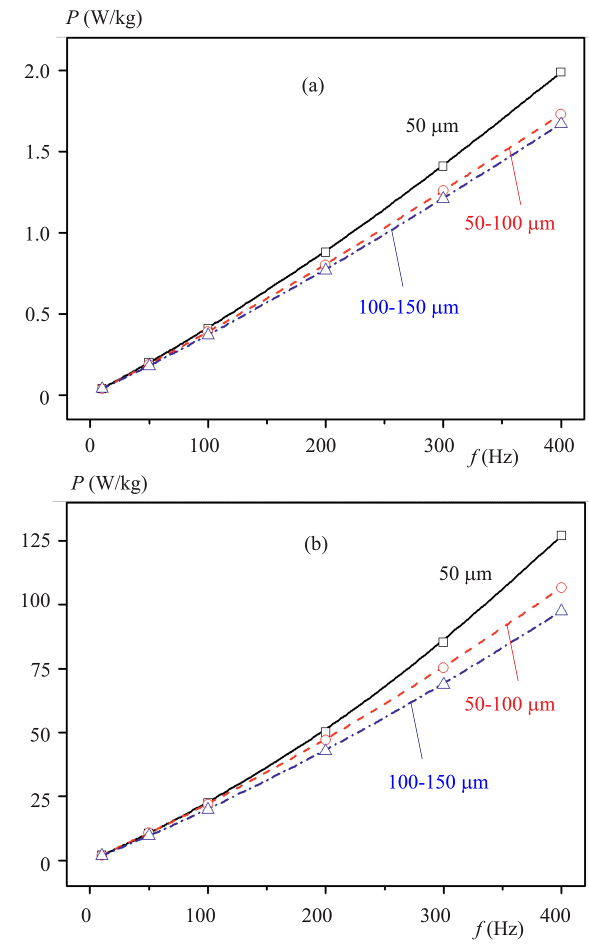

Fig. 3. The influence of fe-grain size on magnetic losses in Fe-polymer composites: (a) – measured at $B_m = 0.1$ T, (b) – measured at $B_m = 1.0$ T

In our research, the magnetic losses were measured using the computer controlled measuring system REMA-COMP C-200 (Magnet-Physik, Dr Steingroever GmbH), presented in Figure 1. The system is based on the wattmeter method. The magnetic field strength H is determined directly from the voltage drop of the magnetizing current across the measuring shunt resistor R.The resulting voltage and the voltage induced in the secondary winding are simultaneously sampled by two fast analog-to-digital converters. Voltage induced in the secondary winding is numerically integrated to calculate the magnetic induction B and the polarization J.The time functions of H and B are used for further evaluation in order to display the hysteresis loop, the loss or permeability curves, *etc* [11,12].

3 Results and discussion

Magnetic losses in the Fe-polymer samples were measured at magnetizing field frequency equal to 10 Hz, 50 Hz, 100 Hz, 200 Hz and 400 Hz, at maximum induction varying from 0.1 T to 1.0 T. The measurements were carried out according to the international IEC 60404 standards, *ie* for sine waveform of magnetic induction inside the sample. The frequency dependencies of magnetic losses, measured at varying level of maximum induction, are depicted in Fig. 2.

In order to evaluate the influence of Fe-grain size on magnetic losses, the loss curves for the samples made of different grain size of iron powder are compared in Fig. 3. The highest values of magnetic losses are observed for the sample made of fine iron powder (<50 μm), whereas the lowest values – for the sample with large Fe-grains. The effect of grain size on magnetic losses is also analyzed for different frequencies of the magnetizing field. For frequency lower than 50 Hz, this effect is negligible. As the frequency increases, the impact of grain size becomes stronger and for 400 Hz the difference in the magnetic loss is about 25%, as is depicted in Fig. 4. Thus, the increase in powder grain size improves the magnetic properties of the Fe-polymer composite, in particular for higher values of magnetic field frequency or maximum induction. The obtained results coincide with the research carried out for other soft magnetic composites, presented in the literature on the subject.

The measured values of magnetic losses for the tested composites are compared to the magnetic loss measurements carried out for commercially used non-oriented

Table 1. Magnetic losses for Fe-polymer composites and non-oriented steels

	Fe-polymer composite			3% Si-Fe	NO steel
	50 μm	50-100 μm	100-150 μm	M330-35A	M530-50A
	Magnetic losses P (W/kg) at 0.5 T				
f = 50 Hz	3.32	3.31	3.07	0.33	0.57
f = 200 Hz	15.48	14.43	13.37	1.95	3.79
	Magnetic losses P (W/kg) at 1.0 T				
f = 50 Hz	10.41	10.63	9.57	1.03	1.81
f = 200 Hz	50.11	46.94	42.77	6.35	13.08

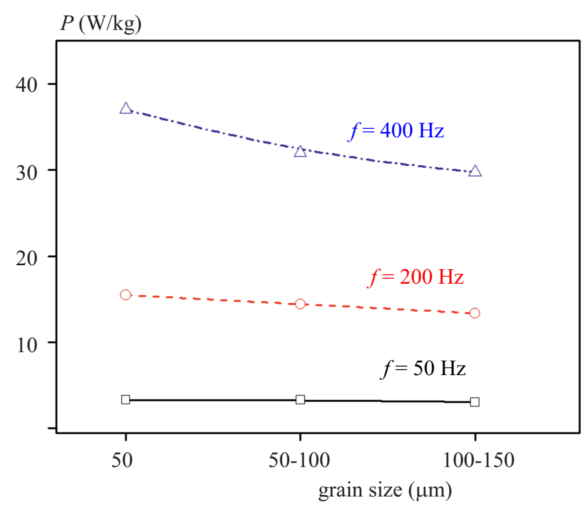

Fig. 4. Magnetic losses versus Fe-grain size in Fe-polymer composites

(NO) steels with two grades: M330-35A and M530-50A, using a Single Sheet Tester. The chosen values of measured losses for these magnetic materials are presented in Tab. 1. Magnetic losses for Fe-polymer composites are about one order of magnitude higher, compared to the corresponding losses for non-oriented steels. However, it should be noted that in the case of Fe-polymer composites magnetic losses were measured for ready-to-used cores, whereas for NO steels - magnetic losses were measured for a single steel sheet of dimensions 500 mm × 500 mm. Thereby, the loss measurements represent circuit properties for composite samples and material properties for NO steels, respectively. It is well known that the forming of toroidal core from NO steel sheets requires technological operations such as cutting and packing of core parts. It introduces mechanical stresses and destroys the material domain structure that deteriorates its magnetic properties. For these reasons, magnetic losses in ready-to-used NO steel cores will be higher than presented in Tab. 1. On the other hand, the use of magnetic composites allows one to produce miniaturized magnetic cores with complicated shapes that are difficult to be produced from electrical steels. Summarizing, Fe-polymer composites - in spite of worse magnetic properties and higher losses - are prospective core materials for miniaturized electric and electronic machines.

The further research will be focussed on the optimization of grain size of iron powder in order to find the best magnetic properties of Fe-polymer composites. Moreover, magnetic losses in these composites will be analyzed using the scaling theory. The scaling theory has been previously applied in the magnetic losses analyzed for electrical steels, amorphous and nanocrystalline ribbons as well as magnetocaloric alloys [13-15], which provided interesting and useful results. The losses scaling should allow us to investigate multiscale behaviour of energy dissipation in Fe-polymer composites; to find universal relations between parameters; and finally to model magnetic composites for different Fe-grain size, excitation conditions or technological parameters.

4 Conclusions

The paper presents initial results of the magnetic losses analysis in self-made Fe-polymer composites. The loss measurements were carried out for three samples made of iron powder with different grain size. The influence of Fe-grain size on magnetic losses was investigated. The lowest value of magnetic losses was obtained for 100-150 μm grains. Magnetic losses in Fe-polymer composite are about one order of magnitude larger, compared to non-oriented electrical steels. However, Fe-polymer composites may be prospective core material due their mechanical properties and the ability to produce miniaturized magnetic circuits of any shape. Further research will focus on the optimization of iron grain size to tailor the magnetic properties of Fe-polymer magnetic composites. In addition, the scaling theory will be used to analyze magnetic losses for these composites.

References

[1] R. Nowosielski, J. J. Wysocki, I. Wnuk and P. Gramatyka, "Nanocrystalline soft magnetic cores", *Journal of Material Process Technology*, 2006, vol. 175, pp. 324-329.

[2] H. Shokrollahi and K. Janghorban, "Soft magnetic composite materials (SMCs)", *Journal of Processing Technology*, 2007, vol. 189, pp. 1-12.

[3] M. Najgebauer and J. Szczygłowski, "Magnetic composites in electric machines", *Elektryka*, 2011, vol. 4 (220), pp. 29-40, 2001 (in Polish).

[4] B. Ślusarek, "New powder magnetic composites application to electric machines and devices", *Tele and Radio Research Institute*, Warsaw, 2012, (in Polish).

[5] B. Ślusarek, J. Szczygłowski, K. Chwastek and B. Jankowski, "A correlation of magnetic properties with material density for soft magnetic composite cores", *COMPEL*, 2015, vol. 34, no.1, pp. 637-646.

[6] M. Najgebauer, J. Szczygłowski, B. Ślusarek, M. Przybylski, A. Kapłon and J. Rolek, "Magnetic composites in electric motors", *Lecture Notes in Electrical Engineering*, vol. 452: Analysis and Simulation of Electrical and Computer Systems, Springer International Publishing, pp. 15-28, 2018.

[7] A. Jakubas, P. Gębara, S. Seme, A. Gnatowski and K. Chwastek, "Magnetic properties of SMC cores products at low compacting temperature", *Acta Physica Polonica A*, vol. 131, pp. 1289-1293, 2017.

[8] "Magnetic Materials - Part 2: Methods of Measurement of the Magnetic Properties of Electrical Steel Strip and Sheet by Means of an Epstein Frame", IEC 60404-2, 2008.

[9] A. Majocha and R. Gozdur, "Bridge method of measurements of the power loss", *Przegląd Elektrotechniczny*, vol. 86, no.4, pp. 79-82, 2010.

[10] R. Gozdur, P. Szczurek and A. Majocha, "Comparison of power loss measurements in grain-oriented steels", *Przegląd Elektrotechniczny*, vol. 93, no.7, pp. 48-51, 2017.

[11] Operating instruction, REMACOMP® C-200", Magnet-Physik, Dr. Steingroever GmbH, Germany.

[12] R. Hiergeist, K. Wagner and G. Ross, "Characterization of Soft Magnetic Materials in AC Magnetic Fields by Digital Methods", *Przegląd Elektrotechniczny*, vol. 93, no.7, pp. 43-47, 2017.

[13] M. Najgebauer, "Fractional scaling of magnetic coercivity in electrical steels", *Acta Physica Polonica A*, vol. 131, no.4, pp. 633- 635, 2017.

[14] R. Gozdur and M. Najgebauer, "Measurements and scaling analysis of power losses La-containing alloys", *Journal of Electrical Engineering - Electrotechnický časopis*, vol. 66, no.7/s, pp. 37-40, 2015.

[15] M. Najgebauer, "Scaling-based analysis and modelling of power losses in amorphous and nanocrystalline alloys", *Acta Physica Polonica A*, vol. 131, no.5, pp. 1025-1027, 2017.

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