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Wide Frequency Range AC Magnetic Properties of Fe-Based Composite Materials

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The aim of this work was to analyze the influence of resin content on contribution of the hysteresis, eddy current and anomalous losses to the total losses in the frequency range from DC to 150 kHz. The samples of composite material were prepared in the form of the ring with outer diameter of 25 mm, inner diameter of 17 mm and height approximately 3 mm and in the form of cylinder with diameter of 25 mm and height approximately 3 mm by a compaction of mixture of iron powder ASC100.29 (90 vol.%) and commercial termoset resins. The DC hysteresis losses were obtained by the measurements of DC hysteresis loops and the total power losses in the frequency range 0.4 Hz–150 kHz from AC hysteresis loops, both at maximum induction 0.05, 0.1 and 0.2 T. The magnetic properties of the composite rings were compared with the properties of the material prepared from the powder supported by Höganäs AB Sweden. By analyzing the frequency dependence of total losses of the Fe-based SMC we found out that hysteresis losses contribute to the total losses as a majority component.

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1. Introduction

Soft magnetic composites (SMC, ferromagnetic powder particles surrounded by an electrical insulating film) is a well known group of materials exhibiting very good soft magnetic properties as low hysteresis losses, low eddy current losses, high permeability at low magnetic field and high saturation flux density [1, 2]. These materials are suitable for various AC and DC electromagnetic applications (cores with three-dimensional isotropic ferromagnetic behaviour for transformers, electromotors and electromagnetic circuits, sensors, actuators, low frequency filters, induction field coils, magnetic seal systems and magnetic field shielding) [3]. Many scientists think that the explorations possibilities of SMC are still not exhausted and forecast further progress leading to the replacement of electrical steel sheets or ferrites in some applications by these composites [3].

The aim of this work was to investigate the influence of resin content on AC magnetic properties of Fe-based composite material to extend possibilities for application of this kind of material at higher frequency.

2. Samples preparation

The SMC samples were prepared by conventional powder metallurgy in form of a ring (for magnetic measurements) and in form of a cylinder (for electric resistivity measurements) [4]. The pure iron powder ASC 100.29, Höganäs AB Sweden [5] was chosen as a ferromagnetic material and a phenol–formaldehyde resin (Bakelite ATM) as an insulator. The particles of the iron powder exhibit (according to the material producer) following particle size distribution: 50 wt% particles have the diameter below 75 μm and 0.9 wt% — above 180 μm .

The bakelite was milled for 3×30 s in a knife mill to obtain the particle size below 100 μm . The experimental samples were prepared by wet homogenisation of 90 vol.% of iron (sample A) and resin with acetone.

The homogenised powder was pressed in a cylindrical die at an uniaxial pressure to obtain compacts in the form of cylinder or ring.

After that the resulting product was cured at a temperature of 165 °C for 60 min in an electric furnace in an air atmosphere.

The termoset phenol–formaldehyde resin covers the iron powder particles, the resin electrically insulates conductive iron particles and creates the mechanical bond after curing [4].

Sample *S* is a reference material, prepared from Somaloy[®] 700 powder (covered by insulating film) provided by Höganäs AB, Sweden by producer-developed technology (compaction at 800 MPa and heat treatment at 530 °C for 30 min in air). Parameters of the samples are in Table.

3. Experimental

The structure of the samples was investigated by scanning electron microscopy (TESLA BS 340). The hysteresis losses were calculated from the minor DC hysteresis loops (maximum flux density of 0.05, 0.1 and 0.2 T) measured by a fluxmeter based hysteresisgraph. AC hysteresis loops were measured by three different AC hysteresisgraphs: in the frequency range 0.4–50 Hz by a fluxmeter based hysteresisgraph, in the frequency range 50 Hz–1 kHz by MATS-2010M and in the frequency range 1–150 kHz by MATS-2010SA at the maximum flux density of 0.05, 0.1 and 0.2 T. The total losses W_t were calcu-

TABLE

Parameters of the samples.

Sample	A	S
volume fraction of Fe [%]	90.0	98.7
outer diameter [mm]	24.00	24.10
inner diameter [mm]	17.87	17.71
height [mm]	2.75	2.81
mass [g]	3.439	3.870
density [g/cm ³]	5.22	6.57
compaction pressure [MPa]	600	800
compaction temperature [°C]	165	530
porosity [%]	13.6	12.4
specific resistivity [$\mu\Omega$ m]	505	4.58
hysteresis loss [J/m ³] at 0.05 T ^a	7	4
hysteresis loss [J/m ³] at 0.1 T ^a	31	17
hysteresis loss [J/m ³] at 0.2 T ^a	1077	67

^a experimental values

lated directly from measured hysteresis loops. The peak relative permeability was calculated from hysteresis loops measured in the frequency range 1–150 kHz at maximum flux density of 0.05 T.

The specific electrical resistivity of the composite material in the form of the cylinder with diameter of about 24 mm and from 2 mm to 4 mm height was measured by the van der Pauw method (assuming to be isotropic in the plane parallel to the cylinder base) [6].

4. Power losses

The total energy losses W_t (in units J/m³) consist of hysteresis W_h , eddy current W_e and anomalous W_a [7–10]:

$$W_t = W_h + W_e + W_a. \quad (1)$$

Hysteresis losses W_h are assumed to be frequency independent and can be obtained by extrapolation the total losses frequency dependence to $f = 0$.

Other possibility how to characterize the frequency dependence of the power dissipation in a magnetic material during the time of 1 s is to use quantity P_t (unit W/kg) by multiplication of Eq. (1) by the factor f/ρ (f — frequency, ρ — density of the material)

$$P_t = W_h \frac{f}{\rho} + P_e + P_a. \quad (2)$$

The eddy current losses P_e can be expressed according to [7, 8] by

$$P_e = \frac{(\pi d B_m f)^2}{\beta \rho_R \rho}, \quad (3)$$

where d is effective dimension (for the material prepared by casting d is thickness of the sample, for laminated material, thickness of the sheet), B_m is maximum flux density, f — frequency, ρ_R — specific resistivity, ρ — density of the material and β — geometrical coefficient. For rectangular cross-section perpendicular to the direction of magnetic flux is

$$\beta = \frac{6}{1 - 0.633(w/h) \tanh(1.58h/w)}, \quad (4)$$

where w is width and h is height of the rectangle [7].

The anomalous contribution at sinusoidal magnetic flux in the material can be expressed as

$$P_a = 8.8 \sqrt{\sigma G S V_0} (B_m f)^{3/2}, \quad (5)$$

where σ is specific electric conductivity of the material, S is cross-section of the material perpendicular to the magnetic flux, B_m — maximum flux density, G and V_0 — parameters depending on the material and magnetization [7].

5. Results

The hysteresis losses of both samples calculated from DC hysteresis loops are presented in Table. The total losses dependences as a function of frequency in the frequency range 0.4 Hz–150 kHz at maximum flux density B_m of 0.05, 0.1 and 0.2 T are depicted in Fig. 1.

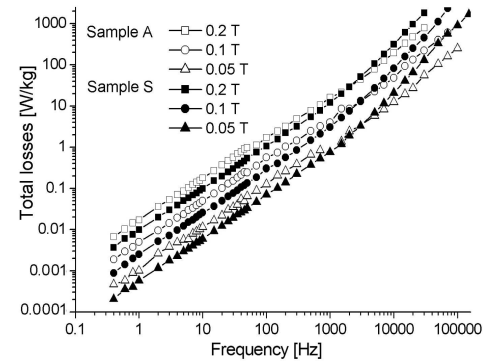


Fig. 1. Total losses P_t as a function of the frequency f for the sample A and S measured at maximum flux density $B_m = 0.05, 0.1$ and 0.2 T in frequency range 0.4 Hz–150 kHz.

The values of total losses as a function of the frequency of the sample A increase less steeply than that for samples S. We assume that lower slope of total losses dependence of the sample A is caused by the lower contribution of the eddy current losses to the total losses due to higher specific resistivity (approximately 100 times) of this sample in comparison with the specific resistivity of the sample S, Table.

The contribution of the anomalous losses W_a (according to Eq. (5) $W_a \sim f^{1/2}$) to the total losses W_t is best observable at low frequency range. In order to detect this contribution we have plotted the total losses in frequency range below 50 Hz. The losses plotted in Fig. 2 for frequency “0 Hz” is hysteresis loss W_h . The fraction of ferromagnetic material (Fe) is larger in sample S, that is why the magnetic contact between ferromagnetic particles is better in this sample, which leads to the lower values of hysteresis loss in comparison with sample A containing relatively large amount of resin.

The peak relative permeability of the sample S, reflecting the slope of the hysteresis loop, is higher than that for sample A, Fig. 3.

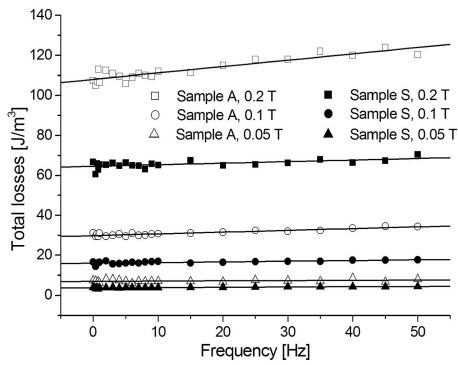


Fig. 2. Total losses W_t as a function of the frequency f for the sample A and S measured at maximum flux density $B_m = 0.05, 0.1$ and 0.2 T in frequency range 0.4 – 50 Hz.

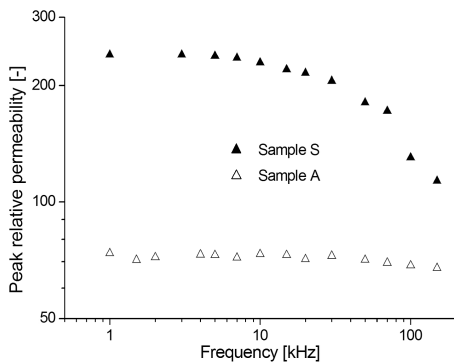


Fig. 3. Peak relative permeability μ_p as a function of the frequency f for the sample A and S calculated from AC hysteresis loops measured at maximum flux density $B_m = 0.05$ T in frequency range 1 – 150 kHz.

The sample A containing larger fraction of nonferromagnetic material exhibits larger value of the inner demagnetization factor N [11, 12]. The iron powder particles create demagnetization field (which is ruled by the mean distance between a pair of ferromagnetic particles), oriented opposite to the external magnetic field H , causing the decrease of the internal magnetic field H_{int} [7]:

$$H_{\text{int}} = H - NM, \quad (6)$$

where M is magnetization of the powder particle.

We suppose that the decrease of the peak relative permeability of the sample S with frequency is caused by the magnetic viscosity of the material [7]. The frequency dependence of total losses of composite material in comparison with metallic compacted powder Fe–Ni based material exhibits lower values and lower slope, which confirms that composite materials are more suitable for high frequency application than metallic materials [13].

6. Conclusion

From the investigation of DC and AC magnetic properties of composite material based on iron powder (90 vol.%) and phenol–formaldehyde resin (10 vol.%), as

insulator we found that the frequency dependence of total losses increases slower than that for reference Somaloy[®] 700 powder based sample. It is caused by the lower contribution of eddy current losses of composite material in which the contribution of hysteresis losses is dominant. The analysis of the total losses for both samples in low frequency range shows no significant contribution of anomalous losses. The frequency dependence of peak relative permeability of the composite material (which reflects the mean distance between a pair of ferromagnetic particles) is lower but practically constant in the whole frequency range 1 – 150 kHz in comparison with that for reference Somaloy[®] 700 material which steeply decreases with the increase of frequency.

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