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Investigation of Magnetization Processes from the Energy Losses in Soft Magnetic Composite Materials

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Soft magnetic composite materials are composed of small ferromagnetic particles insulated from each other. It gives them some very good properties e.g. the magnetic isotropy and low total energy losses at medium to higher frequencies. On the other hand, their structure gives rise to the negative aspects as the inner demagnetizing fields, resulting in some specifics in magnetization processes leading to the worsening of soft magnetic properties, particularly the excess losses increase and a lowering of permeability. The frequency dependence of excess losses, the low and high induction loss components and the inner demagnetization factors of soft magnetic composites were investigated in order to reveal the proportions of the reversible and irreversible magnetization processes. Higher excess losses were observed in samples with smaller particles or higher non-ferromagnetic content (resin+pores), in which the inner demagnetizing fields were higher. It was explained by lower effective number of movable domain walls in those samples, thus less irreversible magnetization processes. This was confirmed by low and high induction loss analysis, where total losses were divided into low and high induction loss components and plotted vs. frequency.

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1. Introduction

Soft magnetic composite (SMCs) materials represent a specific class of ferromagnetic materials, composed of small ferromagnetic particles insulated from each other, resulting in some unique properties as the magnetic isotropy, and relatively low total energy losses at medium to higher frequencies, which make SMCs well suited for various AC and DC electromagnetic applications [1–5]. The structure of SMCs containing non-ferromagnetic components (insulation and pores) give rise to the inner demagnetizing fields [6, 7], which cause that magnetization process is performed more or less independently in each ferromagnetic particle of SMC and hence certain magnetic properties dependences are different from the majority of cast ferromagnets [1–6, 8].

The aim was to investigate the inner demagnetization factors, the frequency dependence of excess losses and the separation of total losses into low and high induction loss components, in order to reveal qualitatively the proportions of reversible and irreversible magnetization processes in SMCs (of different types for comparison).

2. Energy losses and demagnetizing fields

The excess losses W_{exc} are one of the components of the basic classification of the total energy losses W_t [2, 7–10] in ferromagnetic material, besides the DC losses W_{DC} and the classical eddy current losses W_c (where in SMCs [1–5] furthermore the intra-particle and inter-particle flowing of eddy currents is considered). W_{exc} result predominantly from the eddy currents induced when the domain walls are moving [2, 7–9] and depend inversely on the effective number of movable domain walls n [2, 8, 9], $W_{exc} \approx 1/n$. This reveals the proportion of magnetization processes realized by the domain wall displacements, mostly irreversible.

The demagnetizing field H_d is determined by the demagnetization factor N_d [9]. The total demagnetization factor is a sum of the geometrical N_d^{geo} and the inner one N_d^i (N_d^{geo} is zero for ring-shaped magnetic circuit). Especially in SMCs the inner demagnetizing fields are crucial due to presence of non-ferromagnetic components, and were found to significantly influence the magnetization process [1, 6].

Another classification of total energy losses W_t is their separation into low and high induction loss components: W_{AC}^{low} and W_{AC}^{high} (similarly to separation of W_{DC} in [11]). The hysteresis loop-dividing line is at the value of magnetic induction $B_{\mu max}$, where the total permeability reaches its maximum. W_{AC}^{low} stand for the energy dissipation due to domain wall displacements and W_{AC}^{high} due to processes of magnetization vector rotation and domain wall nucleation or annihilation [7, 10–12].

3. Experimental

Samples of sieved granulometric classes of ASC 100.29 iron powder (Höganäs AB, Sweden) were prepared by wet homogenization of iron powder with 5, 10, and 15 vol.% of phenolformaldehyde resin and acetone. Samples were compacted at uniaxial pressure 800 MPa and cured at 165 °C for 60 min in electric furnace in air. Particle size

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distribution measurement showed peaks at 45, 75, 100 and 160 μm (classes F45, F75, F100, and F160) [6, 11]. Second type samples were prepared by mixing Somaloy®(S) powder (Höganäs AB, Sweden) with 5, 10, and 30 wt% of Vitroperm®(VPM) flaky powder (Vacuumschmelze, GmbH & Co. KG, Germany) [5, 13], samples labelled S-VPM (S95-5VPM, S90-10VPM, S70-30VPM), then compacted at 800 MPa and cured at 530 °C for 60 min in electric furnace in air. Dimensions of samples (ring): 2.0–2.7 mm in height, 24 mm in outer diameter and 18 mm in inner diameter. Microscopy investigations of the samples structure can be found in [6, 13]. Properties of samples are in Table I.

DC and AC hysteresis loops were measured by DC and AC fluxmeter-based hysteresis graphs, in order to obtain W_t. Anhysteretic and initial curves were measured using the especially adapted fluxmeter-based setups [6], in order to obtain N_d^i and $B_{\mu max}$. The induction was measured referred to ferromagnetic component of SMC (subtracting resin + pores).

TABLE I

Properties of the samples

Sample	Comp.	Porosity [%]	Density [g/cm^3]	N_d^i [$\times 10^{-3}$]
S to VPM ratio				
S95-5VPM	95:5	1.0	7.61	0.6
S90-10VPM	90:10	4.0	7.33	0.7
S70-30VPM	70:30	13.0	6.62	1.4
iron to resin ratio				
F100-5%	95:5	10.5	6.74	5.1
F45-10%	90:10	17.0	6.00	12.5
F75-10%	90:10	17.5	5.94	11.0
F100-10%	90:10	16.4	6.05	9.8
F160-10%	90:10	15.0	6.10	8.7
F100-15%	85:15	18.0	5.64	11.7

4. Results and discussion

In Figs. 1, 2 the total losses W_t at maximum induction $B_m = 0.5$ T are plotted vs. frequency, in the frequency range DC — 100 Hz, of samples with different resin content (5, 10, 15 vol.%) and samples with 10% of resin differing in ferromagnetic particle sizes. The steeper increase of W_T with frequency was observed in samples with higher resin content and in samples with smaller ferromagnetic particles. We have explained it by the steeper increase of excess losses W_{exc} [7] (analogously the contribution of the eddy current losses in samples with smaller particles is lower, thus cannot be responsible for the steeper increase of W_T). The higher excess losses W_{exc} in the higher resin content samples and the samples containing smaller particles are a result of the lower effective number of movable domain walls n — less domain walls must overcome larger distances and the induced eddy currents accompanying their displacements are higher (this is also the basic reason for higher DC losses W_{DC} in case of lower n). Lower n means the proportion of magnetization processes realized by domain wall displacements (mostly irreversible) is lower. In case of S-VPM samples the increase of W_t is steeper for higher VPM content samples [5], meaning lower effective number of movable domain walls n, too. Lower n is a result of the weakening of magnetic interaction [8, 11] between the ferromagnetic particles, as the inner demagnetizing fields are increased. In SMC this occurs when the particle size is decreasing and when the content of non-ferromagnetic components (insulation and pores) is increasing (in case of S-VPM samples the addition of VPM increased porosity). Values of inner demagnetization factor N_d^i obtained from the anhysteretic magnetization curves measurements [6] are in Table I. The anhysteretic curves of S-VPM samples are plotted in Fig. 3, more tilted curves mean higher N_d^i.

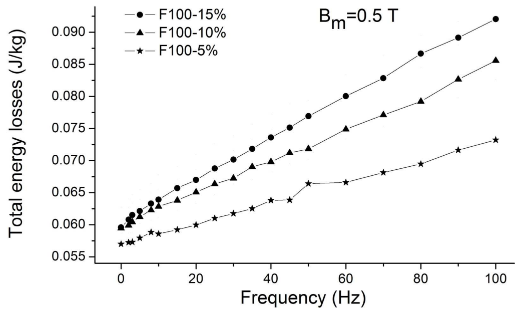

Fig. 1. Energy losses vs. frequency — SMC with 5, 10, 15% of resin.

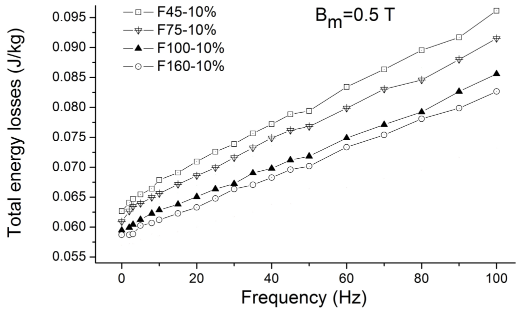

Fig. 2. Energy losses vs. frequency — SMC samples with 10% of resin, differing in ferromagnetic particle sizes.

Total losses at $B_m = 0.8$ T were separated into low induction losses W_{AC}^{low} and high induction losses W_{AC}^{high}, in the frequency range 10 Hz–1 kHz. The induction $B_{\mu max}$ was determined from the initial magnetization curves and similarly from the curves consisting of minor loops maximum points — for every frequency value — all these $B_{\mu max}$ values were approximately the same. The initial curves of S-VPM samples are plotted in Fig. 3. In case of S-VPM samples $B_{\mu max}$ decreases with the increasing porosity: 0.4 T for S95-5VPM, 0.35 T for S90-10VPM and 0.2 T for S70-30VPM (similarly in samples containing the resin $B_{\mu max}$ decreases with the increasing resin content from 0.38 T to 0.22 T [11]). In Fig. 4 W_{AC}^{low} and W_{AC}^{high} are plotted vs. frequency for selected SMC samples, in order to compare the both SMC types. It shows the amount of energy dissipated due to processes of domain wall displacements (W_{AC}^{low}) and processes of magnetization vector rotation and de-nucleation of domain walls (W_{AC}^{high}) [7, 10–12]. W_{AC}^{high} increase much steeper than W_{AC}^{low} in S70-30VPM sample, compared to S95-5VPM sample. It reveals that the magnetization process in the more porous sample S70-30VPM is realized more by processes of magnetization vector rotation than by the domain wall displacements (at frequencies above 50 Hz), qualitatively corresponding to previous conclusions from investigations of excess losses and demagnetizing fields. In sample S95-5VPM as well as in resin containing sample F100-10% values of W_{AC}^{high} and W_{AC}^{low} differ not so significantly. At frequencies below 50 Hz the component W_{AC}^{low} is higher than W_{AC}^{high} in all samples, meaning that below 50 Hz the domain wall displacements dominate over the magnetization vector rotations and domain wall nucleations or annihilations.

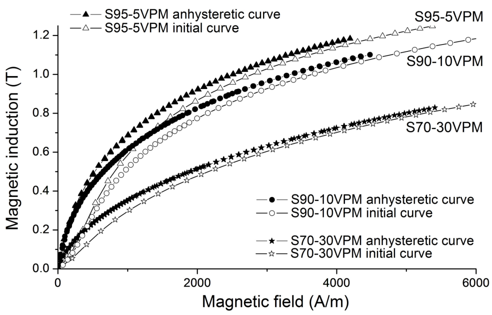

Fig. 3. Anhysteretic and initial curves of S-VPM samples.

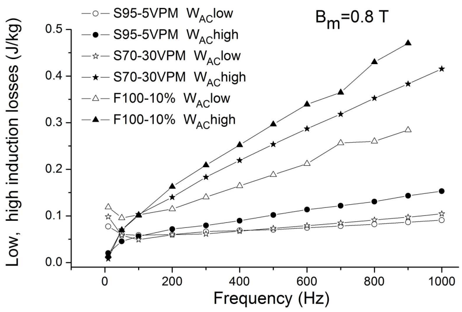

Fig. 4. Low/high induction losses vs. frequency — selected samples.

5. Conclusion

The frequency dependences of excess losses and the separation of total energy losses into low and high induction loss components were studied, together with the inner demagnetization factors, in order to reveal the proportions of reversible and irreversible magnetization processes in soft magnetic composites.

The higher total losses were observed in samples with smaller ferromagnetic particles and in samples with higher resin content, explained by higher excess losses as a result of the lower effective number of movable domain walls. It revealed the magnetization processes is less realized by the domain wall displacements (mostly irreversible), meaning the lower proportion of irreversible processes.

The inner demagnetizing fields were increased with the decreasing particle size and with the increasing resin content, resulting in weakening of magnetic interaction between particles, which reflected in lower effective number of movable domain walls, thus less irreversible processes.

The total losses were divided into low and high induction loss components and plotted vs. frequency. Low induction losses revealed the proportion of energy dissipation due to domain wall displacements, and high induction losses were related to the magnetization vector rotation and the domain wall nucleation or annihilation. These proportions were qualitatively corresponding to the ones found from the frequency dependence of excess losses and the demagnetizing fields investigations.

Acknowledgments

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