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Influence of Ferrite and Resin Content on Inner Demagnetizing Fields of Fe-Based Composite Materials with Ferrite-Resin Insulation

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In this paper, we investigated the influence of ferrite and resin content on inner demagnetizing fields and initial magnetization curves of Fe-based soft magnetic composites with ferrite-resin insulation. The inner demagnetization factor was determined from anhysteretic curves. Samples containing ferrite exhibited lower inner demagnetization factor than those with pure resin insulation. The highest content of ferrite resulted in the increase of porosity, slightly increasing the demagnetization factor. The measured initial curves were recalculated to soft magnetic composites "without pores and resin", meaning that they contains 100% of magnetic material with infinitely low non-magnetic (resin and pores) content. This revealed the high involvement of ferrite particles in magnetization reversal, and their good interaction with Fe particles. Moreover, this confirmed that ferrite particles in the prepared SMCs act as appropriate magnetically active insulator.

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PACS/topics: soft magnetic composite, ferrite, demagnetizing field, anhysteretic curve

1. Introduction

Soft magnetic composites (SMCs) based on Fe exhibit good magnetic properties, such as low eddy current, total energy losses, and relatively high permeability. SMCs are used in various electromagnetic applications, e.g., electric motors, generators, transformers, inductors, filters, frequency modulation chokes, etc. In general, the frequency range available for SMCs spans from hundreds of hertz to MHz [1–3].

The basic structure of SMC forms randomly oriented ferromagnetic particles insulated from each other by an electrical insulator such as a resin. The insulation coating of particles is required to decrease eddy current losses. An ideal coating material should have both good electrical insulating and magnetic properties. Soft ferrites [3, 4] appear to be promising materials with the required properties. However the main disadvantage in using ferrites as coating materials are their mechanical properties which are similar like those of ceramics. Therefore, the resin addition can be favourable to bond the coated Fe particles together.

The SMC structure is advantageous, e.g., for 3D isotropic ferromagnetic behavior or eddy current loss reduction, but it also gives rise to inner demagnetizing fields that lower the permeability. The general sources of demagnetizing fields are volume and surface magnetic poles. In SMCs these fields depend on the amount of non-magnetic content (insulation and pores) and also on the shapes, clustering and distribution of magnetic particles [2, 5]. The successful use of soft ferrite coating would mean reduction of the inner demagnetizing fields, increase of the permeability and decrease of eddy current losses of SMCs [3, 4].

The aim of our study was to investigate the influence of different ferrite and resin content within the insulation in Fe-based SMC on the inner demagnetizing fields and dc magnetization curves.

2. Experimental

Polycrystalline pure iron powder Fe ABC 100.30 (Höganäs AB Sweden [6]) was used as base ferromagnetic material. The size of irregularly shaped particles was ~ 100 μm, in average.

"Ready to press" (pre-sintered) soft ferrite powder FRX-146 (Toda Kogyo Corp. Japan [7]) was chosen for its good magnetic and electrical properties. The composition was 59–63 wt. % of Ni-Zn ferrite and 37–41 wt. % of Cu-Zn ferrite. Ferrite powder was finally heat treated in a microwave furnace at 900 °C for 60 min in ambient air atmosphere. The powder was then ultrasonically pulverized. The coercivity of ferrite powder at room temperature was $\sim$ 300 A/m.

To bond Fe and ferrite particles, the boron modified phenolic resin (PFBR) was used. The synthesis of PFRB was described in [8]. The final mixture of these three main components was performed as follows. The PFRB resin was dissolved in 10 ml of ethyl alcohol, and after then the ferrite particles were added to the solution and dispersed ultrasonically. When suspension was homogenized, the Fe powder was added and mixed until the total

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evaporation of the solvent. The dry mixture powder was pressed to ring-shaped SMC samples, which contained Fe particles coated by ferrite and resin. The compaction was done at 600 MPa in air ambient atmosphere. Compacted samples were cured up to 220 °C with 1.5 °C gradient in air atmosphere.

The initial magnetization curves and anhysteretic curves were measured by the dc-hysteresisgraph based on fluxmeter. The procedure principles and apparatus were described in [5].

3. Results and discussion

Three types of samples were prepared and investigated, each sample with the same volume content of Fe (79 vol. %). The variation was in volume content of the resin (PFBR) and the ferrite (FRX) within the insulation. First sample, labelled "0", was prepared without the ferrite component (number in label corresponds to volume content of FRX). The other two samples contained ferrite with different volume percentage. They were labeled "10.5" and "15.75" with given PFBR:FRX ratios of the order $\frac{1}{2}$: $\frac{1}{2}$ and $\frac{1}{4}$: $\frac{3}{4}$, respectively (Table I). The density and porosity of each sample were calculated from its dimension and mass (densities: $\rho_{\mathrm{Fe}} \sim 7.86$ g/cm^3, $\rho_{\mathrm{PFBR}} \sim 1.14$ g/cm^3, and $\rho_{\mathrm{FRX}} \sim 5.0$ g/cm^3). The filling factor corresponds to magnetic material (Fe+ferrite) volume content.

The linear parts of the anhysteretic magnetization curves (for induction values → 0) of the ring-shaped samples are plotted in Fig. 1. The inner demagnetization factor N_d was calculated from the slope of anhysteretic curves [2, 9] (for the magnetic field → 0) according to the expression [5]:

$$N_d = \left(\frac{B_{\mathrm{mag}}}{\mu_0 H_{\mathrm{ext}}} - 1 \right)^{-1}, \quad (1)$$

where H_{ext} is the applied magnetic field, μ_0 is the magnetic constant, and B_{mag} is the magnetic induction in magnetic component (Fe+ferrite). The calculated demagnetization factors N_d are given in Table I.

The inner demagnetizing fields were found to decrease significantly when the ferrite was added to SMC insulation at $\frac{1}{2}$: $\frac{1}{2}$ of PFBR : FRX fraction (sample 10.5 compared to sample 0). On the other hand, the further

TABLE I

Parameters and properties of SMC samples.

Sample	0	10.5	15.75
Vol. content ratio Fe:PFBR:FRX	79 : 21 : 0	79 : 10.5 : 10.5	79 : 5.25 : 15.75
Density [g/cm^3]	6.17	6.51	6.28
Porosity [%]	4.4	4.95	11.0
Inner demagnet. factor (N_d)	11.7×10^{-3}	4.08×10^{-3}	4.47×10^{-3}
Filling factor of (Fe+ferrite)	0.755	0.851	0.843

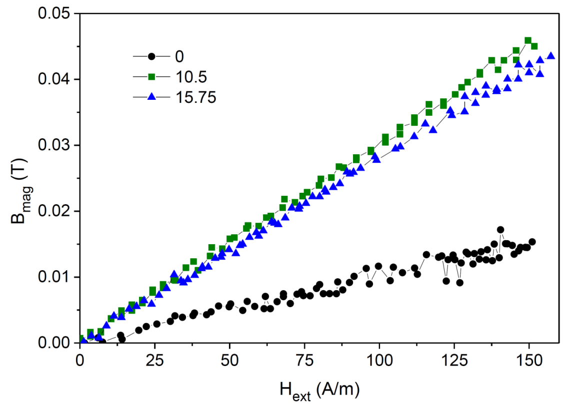

Fig. 1. Anhysteretic curves of Fe based SMC samples with different PFBR resin and FRX ferrite content.

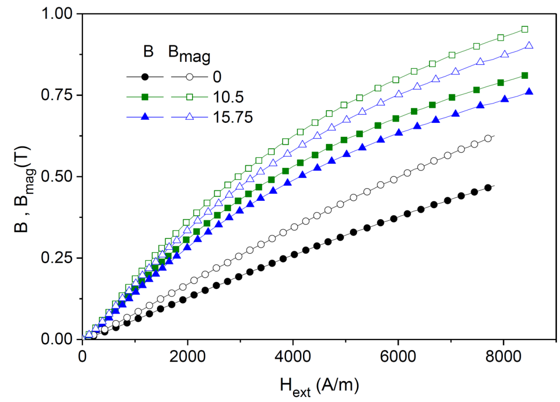

Fig. 2. Initial magnetization curves of Fe-based SMC samples with different PFBR resin and FRX ferrite content (full symbols) and the recalculated initial curves where the magnetic induction (B_{mag}) refers to the magnetic component filling factor (open symbols).

increase of ferrite fraction did not improved more the inner demagnetizing fields. In case of sample with 15.75 vol. % of ferrite, it exhibited higher N_d than the sample with 10.5 vol. % ferrite (the anhysteretic curve of sample 15.75 is slightly more tilted than of sample 10.5), because of increase of porosity. The calculated porosity of sample 15.75 was higher compared to other samples due to increase of gaps between magnetic particles caused by probable worsening of the coating capability of PFBR/ferrite insulation mixture.

Figure 2 shows the initial magnetization curves of composites, i.e., the magnetic induction B in SMC samples vs. the applied magnetic field H_{ext} (full symbols). The tilts of initial curves exhibit the same tendency qualitatively corresponding to the tilts of anhysteretic curves described above. In Fig. 2 also the initial magnetization curves B_{mag} vs. H_{ext} are plotted (open symbols), where the induction B_{mag} represents the induction in magnetic component (Fe+ferrite). This induction B_{mag} was obtained by dividing of induction B by the filling factor of given sample (Table I).

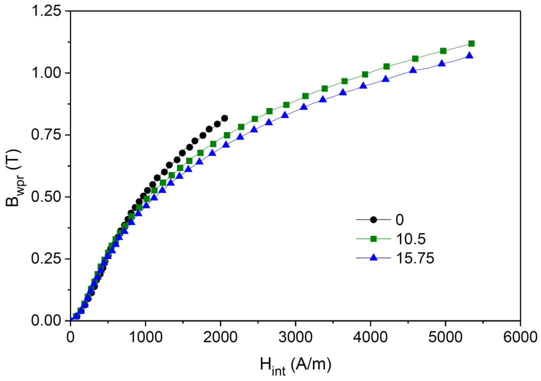

Fig. 3. Initial magnetization curves of SMCs "without pores and resin".

Figure 3 shows the recalculated initial magnetization curves of SMCs "without pores and resin", i.e., $B_{\rm wpr}$ vs. $H_{\rm int}$. The SMC "without pores and resin" contains 100% of magnetic material (filling factor 1), has no pores, and the insulation thickness of magnetic particles is converging to 0 (infinitely thin). Initial curve "without pores and resin" can be recalculated [5]. The magnetic induction in magnetic component $B_{\rm mag}$ is again divided by filling factor in order to express the magnetic flux as the corresponding to 100% magnetic content within the sample volume. Hence, the magnetic induction "without pores and resin", $B_{\rm wpr}$, is obtained. Note, however, that this correction does not describe the real situation, and the values are allowed to be higher than saturation induction. The applied magnetic field $H_{\rm ext}$ is recalculated to the internal field $H_{\rm int}$ [2, 5]:

$$H_{\rm int} = H_{\rm ext} - N_d M = H_{\rm ext} - N_d\left(\frac{B_{\rm mag}}{\mu_0 - H_{\rm ext}}\right), \qquad (2)$$

where M is the magnetization corresponding to $B_{\rm mag}$ vs. $H_{\rm ext}$ anhysteretic curve measurement (Fig. 1) from which the value of N_d was found.

The initial curves "without pores and resin" exhibit quite different tendencies. The steepest slope has the sample 0 containing only Fe particles and pure resin insulation. Next it is followed by sample 10.5 and sample 15.75, respectively — hence exhibiting the lower slope for the increasing volume content of ferrite. It is an expected tendency, as only the magnetic part is seen in this case. Because the iron has higher saturation induction (2.15 T) than the ferrite (0.45 T), the saturation induction of the mixture (Fe+ferrite) decreases with the increasing percentage of ferrite. Nevertheless, we can observe that the initial curves "without pores and resin" are almost identical, from their beginnings until the positions of the maximum derivations of the curves, where in these regions the magnetization process is realized predominantly by domain wall displacements [10]. This revealed the important conclusion that the ferrite particles were highly involved in magnetization reversal and were quite good interacting with Fe particles, confirming that the ferrite particles in the prepared SMCs act as appropriate magnetically active insulator.

4. Conclusion

In this work the influence of different ferrite and resin volume content within the insulation coating on the inner demagnetizing fields was investigated, together with the study of initial magnetization curves of Fe-based soft magnetic composites with ferrite-resin insulation. The significantly low inner demagnetization factor was found for the ferrite containing composites compared to the one with pure resin insulation. On the other hand, the highest content of ferrite resulted in the porosity increase, slightly increasing the demagnetization factor. The initial curves of samples were recalculated to initial curves "without pores and resin" for the composites containing 100% of magnetic material with infinitely thin insulation of particles. This curves "without pores and resin" were found to be almost identical as their beginnings, until the positions of the maxima of derivations of the curves. This revealed that the ferrite particles were interacting with Fe particles (mediating the magnetic flux) and were significantly involved in magnetization reversal, representing the appropriate magnetically active insulator in the prepared SMCs.

Acknowledgments

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