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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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 (Höganas AB Sweden [6]) was used as base ferromagnetic material. The size of irregularly shaped particles was \(\sim 100\, \mu m\), 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 PFBR was described in [8]. The final mixture of these three main components was performed as follows. The PFBR 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 79 : 21 : 0 and 79 : 5 : 10.5, respectively (Table I). The density and porosity of each sample were calculated from its dimension and mass (densities: \( \rho_{\text{Fe}} \approx 7.86 \text{ g/cm}^3 \), \( \rho_{\text{PFBR}} \approx 1.14 \text{ g/cm}^3 \), and \( \rho_{\text{FRX}} \approx 5.0 \text{ g/cm}^3 \)). The filling factor corresponds to magnetic material (Fe+ferrite) volume content.

The linear parts of the anhysteretic magnetization curves (for induction values \( \rightarrow 0 \)) 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 \( \rightarrow 0 \)) according to the expression [5]:

\[
N_d = \left( \frac{B_{\text{mag}}}{\mu_0 H_{\text{ext}}} - 1 \right)^{-1},
\]

where \( H_{\text{ext}} \) is the applied magnetic field, \( \mu_0 \) is the magnetic constant, and \( B_{\text{mag}} \) is the magnetic induction in magnetic component (Fe+ferrite). This induction \( B_{\text{mag}} \) was obtained by dividing of induction \( B \) by the filling factor of given sample (Table I).

| 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 demagnetization factor (\( N_d \)) | \( 11.7 \times 10^{-3} \) | \( 4.08 \times 10^{-3} \) | \( 4.47 \times 10^{-3} \) |
| Filling factor (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.

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 increase of ferrite fraction did not improve 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 \( H_{\text{ext}} \) (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 \( B_{\text{mag}} \) vs. \( H_{\text{ext}} \) are plotted (open symbols), where the induction \( B_{\text{mag}} \) represents the induction in magnetic component (Fe+ferrite). The induction \( B_{\text{mag}} \) was obtained by dividing of induction \( B \) by the filling factor of given sample (Table I).
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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