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Study of Reversible and Irreversible Magnetization Processes Proportions of Fe-MgO Soft Magnetic Composites

M. Jakubčin[a,*], Z. Birčáková[b], P. Kollár[a], J. Füzer[a],
R. Bureš[b] and M. Fáberová[b]
[a]Institute of Physics, Faculty of Science, P.J. Šafárik University, Park Angelinum 9, 04154 Košice, Slovakia
[b]Institute of Materials Research, Slovak Academy of Sciences, Watsonova 47, 04001 Košice, Slovakia

Fe based soft magnetic composite samples with 2 wt%, 3 wt% and 5 wt% of MgO insulator particles were prepared. The magnetic field dependence of the differential and the reversible permeability were measured for all samples by modified DC hysteresisgraph. Subsequently, we determined the irreversible permeability, and calculated the proportions between reversible and irreversible magnetization processes. The study revealed that the lower content of MgO in samples caused the increase of irreversible magnetization processes proportions. It is a result of the lower inner demagnetizing fields, improving magnetic interactions between ferromagnetic particles, leading to higher numbers of active (moveable) domain walls, and hence facilitating the magnetization reversal.

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1. Introduction

Soft magnetic composites (SMCs) are ferromagnetic materials with unique soft magnetic properties as 3D magnetic flux, relatively high saturation magnetization, and low core losses [1]. SMCs consist of ferromagnetic powder particles coated by thin layer of insulation. Reduction of eddy current losses in SMCs allows for SMC applications as transformer cores, parts of the electromotors, sensors, etc., in a wide range from medium to high frequencies. Magnetic properties of SMCs are closely related with their specific structure. Relatively high inner demagnetizing fields, which are produced by magnetic poles of ferromagnetic particles, lead to more difficult magnetization reversal. To suppress this effect the distances between particles have to be shorten. It can be realized, in fact, by thinning of the insulation layer. The magnetic interactions between particles are then enhanced [2].

The SMC components are produced by powder metallurgy methods, most commonly by high pressure compaction [1]. Residual mechanical stresses in ferromagnetic powder particles make magnetization reversal more difficult and cause the higher core losses, if these are not eliminated by annealing [3]. The use of resin coatings in SMC usually does not allow the heat treatment at temperatures above 200 °C [4]. In last few years the use of inorganic coatings becomes popular. The magnetic composite Fe-MgO is such an inorganic system, well known for his fine magnetic properties and tolerance to high temperature heat treatment [5, 6].

We experimentally studied the proportion of reversible and irreversible magnetization processes in Fe-MgO SMCs, especially the irreversible domain wall displacements proportion, as a function of magnetic field along DC magnetization curves. The aim of this work was to contribute to better understanding of magnetization processes in SMC materials.

2. Experimental

The iron powder ASC100.29 with average particle diameter of 100 μm was mixed with MgO insulator powder with average particle diameter of 1 μm in acoustic resonance mixer Resodyn. Thus, the samples with 2 wt%, 3 wt% and 5 wt% of MgO were prepared. The powders were cold compacted by uniaxial pressure of 600 MPa to obtain ring-shaped samples with the inner diameter $\approx$ 18 mm and outer diameter $\approx$ 24 mm. The samples were microwave heat treated at 600 °C for 15 min in air atmosphere.

We measured the magnetic field dependence of the differential permeability and the reversible permeability by the modified DC hysteresisgraph (the DC and small AC magnetic field were applied concurrently), with lock-in amplifier detecting of small values of AC induction [7, 8]. The differential relative permeability μ_{diff} along DC hysteresis loops and initial curves was determined at point (H_0, B_0) according to the definition

$$\mu_{\mathrm{diff}} = \frac{1}{\mu_0}\left(\frac{\mathrm{d}B}{\mathrm{d}H}\right)_{H_0,B_0}, \tag{1}$$

where B is the magnetic induction and H is the external magnetic field. Differential relative permeability is reflected by the sum of the reversible and the irreversible magnetization processes, namely

$$\mu_{\mathrm{diff}} = \mu_{\mathrm{rev}} + \mu_{\mathrm{irrev}}, \tag{2}$$

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[*] corresponding author; e-mail: milos.jakubcin@gmail.com

where μ_{rev} and μ_{irrev} are respectively the reversible and irreversible permeability [8]. In experiment one can determine μ_{diff} and μ_{rev}. Then, the proportion of the irreversible magnetization processes within all magnetization processes (k_{irrev}) can be expressed as

$$k_{\mathrm{irrev}} = \frac{\mu_{\mathrm{irrev}}}{\mu_{\mathrm{diff}}} \times 100\%. \qquad (3)$$

3. Results and discussion

The DC hysteresis loop at maximum induction of 0.8 T of the sample Fe-MgO 2% in Fig. 1 was chosen as a representative example showing relationship of the irreversible magnetization processes proportion to magnetic induction — $k_{\mathrm{irrev}}\,(B)$ dependence. Figure 2 presents the $k_{\mathrm{irrev}}\,(B)$ dependence along the initial magnetization curves up to 0.6 T. The $k_{irrev}\,(B)$ dependences along DC hysteresis loops at maximum induction of 0.2 T and 0.6 T are shown in Fig. 3 and Fig. 4.

As we can see in Fig. 1, the $k_{\mathrm{irrev}}(B)$ dependence has maximum values near the coercive field (zones 2 and 4). For DC hysteresis loop at saturation induction (~ 2.15 T for Fe) the maximum values of k_{irrev} can be located at the inflection points of the hysteresis loops coincident to the coercivity. In zone 2–3 at hysteresis loop (Fig. 1) the irreversible domain wall displacements appear in a high proportion in the magnetization process. When the direction of external field is switched leading to the increase in zone 3–4 (Fig. 1), the most probable process that takes place is the reversible rotation of magnetization vector of domains, as long as the volumes of the domains with opposite oriented magnetization vector start to grow [9]. This magnetization processes sequence causes the discontinuity of the $k_{\mathrm{irrev}}(B)$ curve along the minor (unsaturated) hysteresis loops, contrary to the saturated hysteresis loop where the $k_{\mathrm{irrev}}(B)$ dependence is the continuous curve due to the disappearance of domain structure at saturation induction.

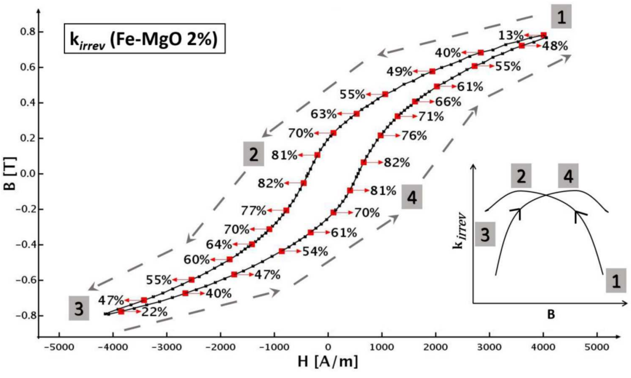

Fig. 1. Proportion of the irreversible magnetization processes k_{irrev} of sample Fe–MgO 2% along the DC hysteresis loop at maximum induction B of 0.8 T, with the illustration of the direction of magnetization reversal (inset).

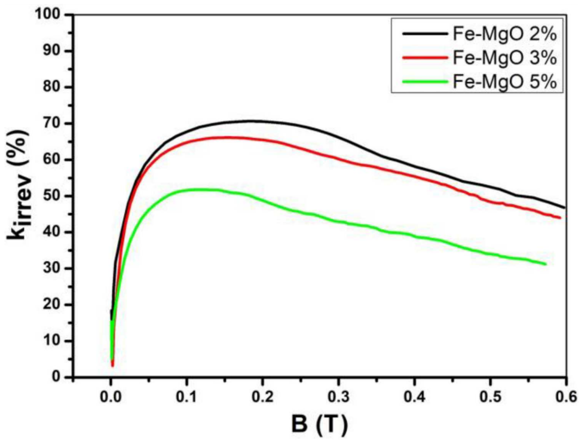

Fig. 2. Dependences of the proportion of irreversible magnetization processes k_{irrev} on magnetic induction B along the initial magnetization curves up to 0.6 T.

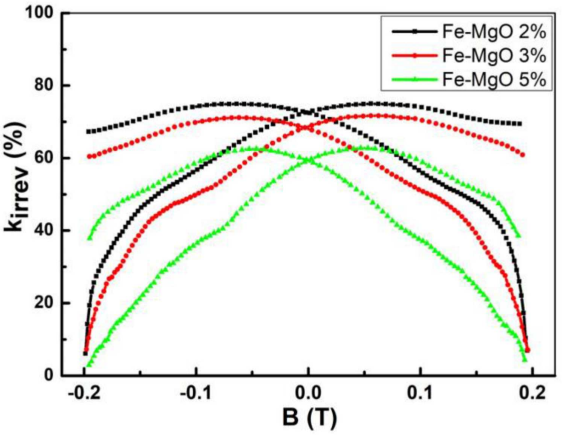

Fig. 3. Dependences of the proportion of irreversible magnetization processes k_{irrev} on magnetic induction B along the DC hysteresis loops with maximum induction 0.2 T.

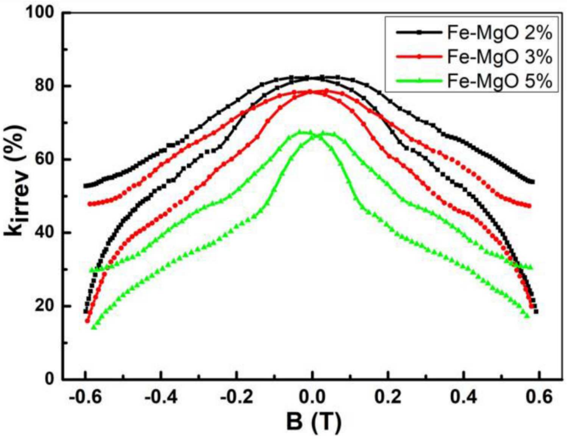

Fig. 4. Dependences of the proportion of irreversible magnetization processes k_{irrev} on magnetic induction B along the DC hysteresis loops with maximum induction 0.6 T.

TABLE I

Values of density and ferromagnetic filler content (filler factor) of Fe-MgO samples.

Fe-MgO	2 wt%	3 wt%	5 wt%
Density [g/cm^3]	6.7	6.5	6.2
Filler factor [%]	83	80	75

Table I shows the decrease of both, the density and ferromagnetic filler content of Fe-MgO samples, with higher MgO content. The results in Figs. 2–4 expose that higher content of insulator in Fe-MgO based composites causes the decrease of k_{irrev} values at the magnetization curves. We assumed this tendency results from weaker interparticles interactions, which in turn are caused by higher inner demagnetizing fields in samples with higher amount of MgO. Overall this leads to more difficult magnetization reversal.

In the majority of soft ferromagnetic materials the irreversible magnetization processes concern mostly the irreversible domain wall displacements (Barkhausen jumps), in contrast with the irreversible rotations of magnetization vector which occur negligibly [9]. Sample with 2% MgO exhibits k_{irrev} more than 80% at the coercive field points of the loops, where maximum induction is of 0.6 T and 0.8 T. It is because the high numbers of domain walls are active (moveable) during magnetization reversal. In [8] there was found that some of investigated iron based SMCs materials with lowest H_c can exhibit k_{irrev} near to 90% (at coercive field) of the loops with maximum induction of 0.8 T.

4. Conclusion

We studied the reversible and irreversible magnetization processes proportions along DC magnetization curves in Fe-MgO SMC materials, by means of the measurement of the reversible permeability. We found out the descending proportion of the irreversible magnetization processes proportion with the increasing amount of insulator in SMCs. This tendency is a consequence of the increasing inner demagnetizing fields with higher content of MgO. Then, the magnetic interactions between ferromagnetic particles become weaker, the numbers of active (moveable) domain walls become lower, and thus making the magnetization reversal more difficult. This effect can be explained by branching of the paths for the magnetic flux oriented originally in the direction of applied magnetic field with arms of magnetic field around ferromagnetic particles oriented in various direction with circular magnetic field produced by toroidal coil, when the demagnetizing factor increases.

Acknowledgments

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