MAGNETIC PERMEABILITY OF SOFT MAGNETIC COMPOSITES

Ján Füzer[1], Samuel Dobák[1], Ľuboslava Ďáková[1], Peter Kollár[1], Magdaléna Strečková[2], Radovan Bureš[2], Mária Fáberová[2]

[1] Institute of Physics, Faculty of Science, P. J. Šafárik University, Košice 041 54, Slovakia

[2]Institute of Materials Research, Slovak Academy of Sciences, Watsonova 47, 043 53 Košice, Slovakia

E-mail: jan.fuzer@upjs.sk

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1. Introduction

Soft magnetic composites (SMCs), which are used in electromagnetic appliances, e.g. electric motors, transformers, sensors and other inductive devices, consist of ferromagnetic powder particles surrounded by an electrical insulating material. These composite materials offer unique properties such as three-dimensional isotropic ferromagnetic behaviour, lower weight and size, very low eddy current loss, relatively low total core losses at medium and high frequencies, high electrical resistivity and good relative permeability [1].

Insulation layer between magnetic powder particles should ensure a high electrical resistivity minimizing the overall magnetic losses. The dielectric materials used for the insulation can be selected from organic polymeric resins [2], or inorganic materials such as metals, oxides, phosphates, or silicates [3, 4]. A number of different methods are used to prepare SMCs using ferrites (spinel ferrites) as an insulating layer [5, 6]. A comprehensive theoretical approach proposed by Y. Pittini-Yamada et al. [7] reveals the important factors at the preparation of SMCs, e.g. particles orientation, porosity volume and composite matrix properties that significantly govern the interactions between particles.

Recently, we have presented [8] the results regarding SMC cores with different ferromagnetic materials and dielectric materials. Therefore, the aim of this paper is to compare the complex permeability spectra of a series of SMCs samples differing in ferromagnetic particles and dielectric matrix. The results are explained and discussed with respect to physical phenomena associated to the heterogeneous nature of SMCs.

2. Experimental methods

The bulk ring-shaped samples were prepared by standard route of powder metallurgy. Precursor materials were (i) high-purity Fe powder, (ii) powder of spherical FeSi particles and (iii) nanocrystalline powder prepared from nanocrystalline thin ribbons produced by rapid solidification. Particles size in all powders ranges from several μm up to some hundreds μm. So-obtained materials were compacted by uni-axial pressure in original pure state or blended with two different polymeric resins into rings. Resin 1 is a phenol-formaldehyde resin chemically modified with SiO_2 [9] and Resin 2 is a phenol-formaldehyde resin available from the ATM, Germany.

Complex permeability spectra were measured on ring samples with few turns of insulated wire by impedance spectroscopy using an impedance analyzer HP 4194A by means of a series equivalent circuit as described elsewhere [10]. The amplitude of excitation ac magnetic field was kept at very small defined values of about 0.5 A/m to ensure the regime of initial permeability. Electrical resistivity was measured by standard four-point probe method.

3. Results and discussion

The details on composition, specific electrical resistivity, quasi-static of real permeability and relaxation frequency of investigated SMC samples are collected in Table 1. Further information on the samples can be found in listed Refs. [11-13]. Three ferromagnetic powder materials used as core differ significantly in their morphology. The Fe (ASC 100.29) powder has the typical rugged morphology, FeSi powder is spherical and flakes of $Fe_{73}Cu_1Nb_3Si_{16}B_7$ are very sharp and rectangular. It is worthy to notice that any imperfections like cracks, foaming of the resins or exfoliation of the particles from the surface were not observed.

Tab. 1. *Composition, specific electrical resistivity, quasi-static of real permeability and relaxation frequency in studied SMCs.*

Sample	Ferromagnetic part		ρ [μΩ.m]	$\mu_{r,\,DC}'$ [-]	f_C [kHz]
	Composition	Amount [%wt.]			
Fe/3% resin1	Fe	97	1349	65.7	3475.0
Fe/5% resin2	Fe	95	361	64.6	806.1
FeCuNbSiB/4% resin1	$Fe_{73}Cu_1Nb_3Si_{16}B_7$	96	1754	40.8	3430.0
FeSi/4% resin1	$FeSi_3$	96	3530	39.9	10 904.0
Fe/15% resin2	Fe	85	2566	33.5	1817.2

Fig. 1 shows the frequency dependences of the complex permeability components in all samples prepared by compaction of different ferromagnetic powders. The real component of permeability, μ_r', is first fairly constant with frequency and then decreases rather rapidly at higher frequencies. On the other hand, the imaginary component, μ_r'', increases at the frequencies at which the real component, μ_r', is decreasing sharply. It reaches a maximum at about where the real permeability has dropped to about one half of its initial value. As the definition of the complex permeability implies, these curves are coupled in that the increased losses due to the increase in frequency results in lowering the permeability.

The different magnetization processes (reversible domain wall movements, irreversible domain wall displacements and spin rotation) possess different time constants, so-called relaxation time, τ_r, which is responsible for the dynamics of the magnetization process. The results show a broad range of variations in obtained curves rising from differences in powder particles morphology, structure and amount of dielectric phase. They differ in two important parameters: (i) in quasi-static value of real permeability component, $\mu_{r,\,DC}'$ determined from the extrapolation of low-frequency part real part of complex permeability to $f \to 0$ (Fig. 1a), and (ii) in a relaxation frequency (f_c) observed as a position of a single peak in imaginary part of complex permeability (Fig. 1b). These extracted values for all samples are listed in Table 1.

For all samples the real part of complex permeability exhibits stable behaviour up to frequency of 100 kHz. With the increasing specific electrical resistivity the peak of the imaginary part is shifting to higher frequencies.

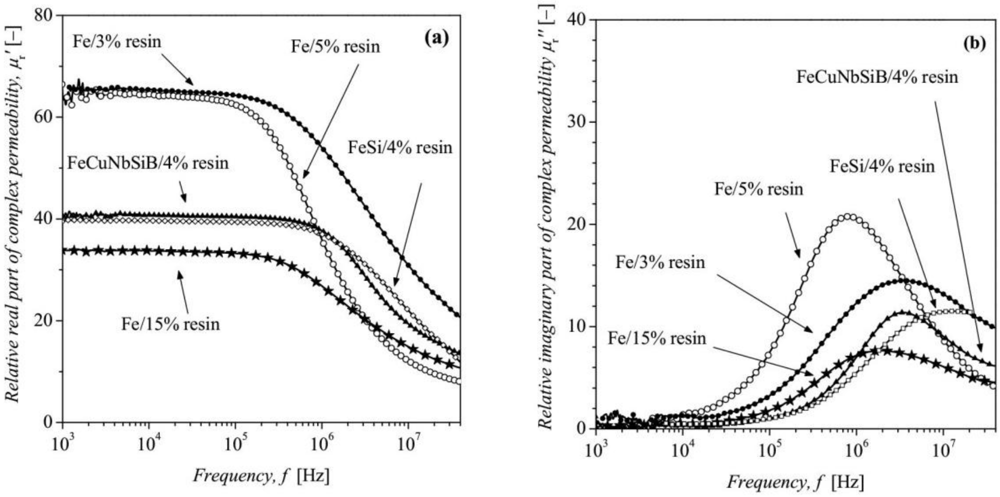

Fig. 1: *Relative real (a) and imaginary (b) parts of complex permeability spectra in the different soft magnetic composites*

The electrical resistivity is a significant term in eddy current related damping of domain wall motion. The larger resistivity extends the large permeability to higher frequencies where eddy currents (classical and those due to domain wall motion) dominate the losses. The larger role of rotation and lower one of domain walls is ascribed to the stronger demagnetizing effects inside the heterogeneous structure of composite materials that make processes connected to domain walls more difficult. The real part of permeability strongly depends on the density, number of pores, non-magnetic phase, crystal anisotropy and magnetic anisotropy. Due to the demagnetizing field, the permeability is related to the shape of the particles.

4. Conclusion

The real and imaginary permeability components of bulk materials prepared from different soft magnetic powders and dielectric insulator by powder metallurgy have been measured covering a wide range of magnetizing frequencies. It has been found permeability dispersion due to the magnetizing frequency influence on magnetization processes in studied soft magnetic composites. It has been demonstrated that the different content of dielectric resin and the different ferromagnetic particles inside the composite significantly affect the prevalent magnetization process. The role of rotation on the dynamic magnetization reversal increases with higher specific resistivity.

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