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MEASUREMENT OF SELECTED ELECTROMAGNETIC PARAMETERS OF FERRITE POLYMERS

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The selected properties of the soft magnetic composite material consisting from ferrite particles in non-magnetic matrix were measured. The complex permeability spectra were used as effective parameter of prepared and measured samples. The properties of composite may be modelled for estimation of measured data.

Keywords: sintered ferrite, composite material, complex permeability, complex permitivity

1 INTRODUCTION

The electromagnetic properties and losses in a given magnetopolymer are extremely difficult to categorize in the general case [1, 2], and here, we will be satisfied with simple treatment. The optimum value of permeability and low power losses are dominant characteristics of magnetically soft composites. The materials have frequency dependent permeability and permittivity. The account is given on permeability and permittivity modelling and we are interesting only with very high magnetic filler concentration composites. Then effective permeability μ_e and permittivity ε_e of composite was choosing as effective parameter for composite properties study. The approach was made at first as a quasistatic problem and second the frequency dependent complex permeability or permitivity was taken to account.

2 MODEL DESCRIPTION

For two components composite the model consider that the magnetic particles are surrounded by polymer layers with very low magnetic susceptibility [3]. The distribution of magnetic filler particles in the polymer matrix may have generally a heterogeneous structure of arrangement. In spite of that, in the first approach one can use the model based on the simple (prismatic) shape of particles and the simple structure of their arrangement for the simulation of electromagnetic properties of magneto-composite. The schematic configuration is shown in Fig. 1. This regular array of ferrite particles considers an uniform plane wave propagation through magneto–composite. The propagating is possible by means of dominant transverse electromagnetic TEM mode for which $E_x = 0$ and $H_x = 0$. The permeability model proposed in [3] may be used also for permittivity behaviour description.

The elementary cell of the composite consisting of the prismatic particles surrounded by the polymer from three sides is suitable also in this case. The elementary cell of idealized composite is in Fig. 1a. The Maxwell integral laws of Faraday and Ampere applicable to the TEM mode obeying the conditions just noted can be used in the model. The elementary cell of idealized composite structure was modelled using series-parallel magnetic circuit, Fig. 1b, from point of view magnetic field $\vec{H}$ direction. There is particle reluctance in series connection together with the polymer gap reluactance and both are bridged by a parallel reluctance of the matrix layer around the particle. The main assumption was that a gap length d << D (particle size). The distribution of magnetic fluxes Φ_g and Φ_m passing through both parallel circuit branches is homogeneous. These assumptions can be acceptable at relative high particle concentration. By the above assumption the effective permeability is as follows

$$\mu_e = \left\langle \mu_i \frac{(1+\eta)^2 \kappa_v}{1+\eta\mu_i} \right\rangle + \left\langle 1-(1+\eta)\kappa_v \right\rangle = \left\langle 1 + \frac{\chi_i (1+\eta)^3 (1+\sigma)}{1+\mu_i \eta} \kappa_v^2 \right\rangle \tag{1}$$

where < > means a statistical mean value and μ_i is the intrinsic permeability of particle. To better view the problem composite structural parameters η, σ and volume particle fraction (concentration) κ_v were introduced. Demagnetising parameter $\eta = d/D$ and area (or cross-sectional) parameter $\sigma = S_m/S_g$. The cross-sectional area of particle and polymer are S_g and S_m, respectively. All structural parameters of prepared composites have statistical character. It was estimated, that dominant role in increasing the μ_e value has demagnetising structural parameter η and κ_v.

From point of view electric field $\vec{E} \equiv E_y \vec{u}_y$ vector the elementary cell may be also modelled by a series-parallel dielectric circuit, Fig. 1b. In $\vec{E}$ direction, the Maxwell's (Faraday's) integral law can be used in the model. The electric flux Ψ_e passing through elementary cell may be divided into two parts; one Ψ_g passes through particle and second flux Ψ_m flows out of particle. For this case, the cross-sectional area of particle and a pure polymer part of cell are S_f and S_m, respectively.

By above-mentioned assumption, one may derive the effective permeability formula as example

$$\varepsilon_e = \left\langle \frac{\varepsilon_m \varepsilon_g}{\varepsilon_m + \varepsilon_g \eta_e} \cdot \frac{1+\eta_e}{1+\sigma_e} + \varepsilon_m \frac{\sigma_e}{1+\sigma_e} \right\rangle \tag{2}$$

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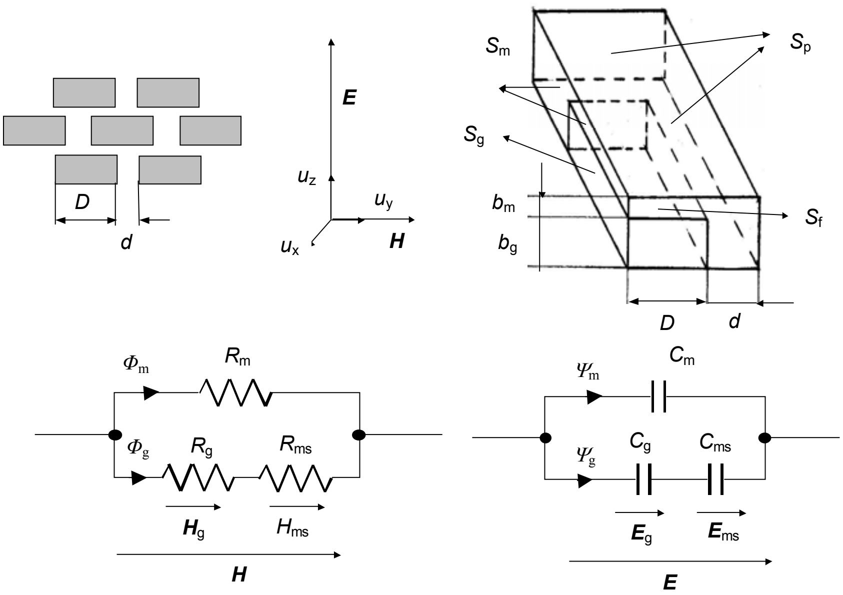

Fig. 1. The model of filler particles structure arrangement in polymer matrix: array of particles and elementary cell of composite (a), models of magnetic and dielectric circuit (b).

where ε_m and ε_g are the intrinsic permeability of matrix and particle. There were introduced dielectric structural parameters η_e and σ_e. Depolarizing parameter is $\eta_e = b_m/b_g$, where the average size of ferrite particles b_g and the average thickness of matrix layer b_m are characteristic dimensions in electric intensity direction $\vec{E}$. Cross-sectional electric parameter is $\sigma_e = S_p/S_f$, where particle area S_f and pure matrix area S_p (without S_f) characterize electric flux density of elementary composite cell in $\vec{E}$ direction. Although the ferrite particle size and the polymer layer volume have distributions, we consider only the average values represented in Fig. 1. Assuming that the ferrite particles with uniform size are homogeneously disturbed in the composite, the relations between volume particle fraction (concentration) κ_v and electromagnetic structural parameters (η, σ, $\eta_e\sigma_e$) of composite may be presented as

$$[(1+\eta)(1+\sigma)]^{-1} = \kappa_v = [(1+\eta_e)(1+\sigma_e)]^{-1} \qquad (3)$$

The magnetopolymer have frequency depend polarisation or permitivity due to both ferrite and polymer polarisation. For microwave to millimetre wave frequencies, the dispersion and absorption in dielectrics may be described by Debye relaxation equation. In addition, if we will to take account the Eq. 2, then the complex permittivity spectra of composite may be approximated by

$$\tilde{\varepsilon}(\omega) = \frac{\varepsilon_m \varepsilon_g (1+\eta_e)^2 \kappa_v}{(\varepsilon_m + \varepsilon_g \eta_e)\left[1 + j\omega\tilde{\tau}_e\right]} + \frac{\varepsilon_m\left[1 - (1+\eta_e)\kappa_v\right]}{(1 + j\omega\tilde{\tau}_e)} \qquad (4)$$

where ω denotes the operating angular frequency and non-relaxation parameter ε_∞ was neglected. The one may present a lot of relaxation time distribution. The hypothesis of distribution of relaxation times, although a natural one to consider leads to general distribution formula with one disposable complex time parameter $\tilde{\tau}_e(\omega)$. The distribution function is nothing more than a means of expressing the experimental results which is equivalent to the circular arc locus corresponding to Debye relaxation equation. In general, $\tilde{\varepsilon}(\omega)$ spectrum of both components of composite may be approximated by (4) with distinguish parameters $\tilde{\tau}_e(\omega)$. In the first approximation, we will accept that ε_g of ferrite have dominant roll and dielectric relaxation properties of polymer are neglected here after.

From the thermodynamic aspect for polycrystalline ferrites and polymer ferrite composites the permeability spectrum can be described by superposition of two components in complex domain, that can be attributed to two types of processes associated with relaxation and resonance effect. $\tilde{\mu}(\omega) = \tilde{\mu}_r(\omega) + \tilde{\mu}_0(\omega)$.

We assume that both relaxation $\tilde{\mu}_r(\omega)$ and resonance $\tilde{\mu}_0(\omega)$ components may be attributed to two types of magnetizing processes: the spin rotation and domain wall motion $\tilde{\mu}(\omega) = 1 + \tilde{\chi}_{dw}(\omega) + \tilde{\chi}_{sp}(\omega)$. The spin rotation complex susceptibility component $\tilde{\chi}_{sp}$ and the domain wall component $\tilde{\chi}_{dw}(\omega)$ are of the relaxation and/or the resonance type. Magnetisation processes due to rotation of magnetisation are calculated using the electromagnetic torque equation. As example, starting form Landau-Lifshitz equation, Kittel calculated the frequency dependence of complex initial susceptibility for sintered ferrite

$$\tilde{\chi}_{sp} = \frac{\chi_i\left[\omega_0^2 + (\Lambda/\chi_0)(j\omega + \Lambda/\chi_0)\right]}{\left[\omega_0^2 + (j\omega + \Lambda/\chi_0)^2\right]} \qquad (5)$$

with resonance frequency $\omega_0 = |\gamma| H_{ef}$, where γ is the gyromagnetic ratio. The quasistatic initial susceptibility at rota–tion process is χ_i and the mean rotation susceptibility χ_0 is roughly equal to χ_i. The parameter $\Lambda = |\gamma|\alpha J_s$, defined spin relaxation frequency in LL equation with damping coefficient α and saturated magnetic polarisation J_s. If one selects the term$(\mu_e - 1)$ from Eq. 1 and this term substitutes to χ_i in Eq. 5, then $\tilde{\chi}_{sp}$ is rearranged to estimate of ferrite polymer composite. Substitution of rearranged $\tilde{\chi}_{sp}$ to $\tilde{\mu}_{sp} = 1 + \tilde{\chi}_{sp}$, we obtain the complex permeability spectra of composite corresponding to the rotational magnetisation. For weak damping $\Lambda << |\gamma| J_s$ the Eq. 5 exhibits resonance character and $\tilde{\mu}_{sp} = \tilde{\mu}_0$. For strong damping $(\Lambda >> |\gamma| J_s)$ the Eq. 5 exhibits relaxation behaviour with $\omega_r = \Lambda / \chi_i$ and $\tilde{\mu}_{sp} = \tilde{\mu}_r$.

For domain wall motion magnetising process with resonance phenomena of oscillating walls and by acceptation of Eq. 1 the permeability model given in [4] can be modified for the magnetocomposite as

$$\tilde{\mu}_{dw}(\omega) = 1 + \frac{\chi_i (1+\eta)^3 (1+\sigma)\kappa_v^2}{(1+\mu_i \eta)\left[(1-(\omega/\omega_0)^2 + j\,\omega/\omega_0)\right]} \qquad (6)$$

where ω_0 is now angular resonance frequency connected with domain wall mass. The relaxation frequency ω_r is connected with relaxation time T of domain wall motion in this magnetisation processes that may be determined from magnetic complex time parameter $\tilde{\tau}(\omega)$. Equation 6 can exhibit resonance and relaxation character.

3 RESULTTS AND DISCUSSION

The electromagnetic properties of sintered ferrites and ferritepolymer composite samples were measured using low impedance analyzer in frequency range 1 MHz to 1.66 MHz by a coaxial line cell [5]. For sintered MnZn ferrite the frequency measured spectra of $\tilde{\mu}(\omega)$ are plotted as locus in the complex plane Fig. 2a where real component $\mu_1(\omega)$ is plotted against the imaginary com– ponent $\mu_2(\omega)$. The real part $\mu_1 \approx 500$ in the low frequency region begins to decrease at 0.2 MHz and reaches about $\mu_1 \approx 10$ at 200 MHz. On the other hand, the imaginary part $\mu_2(\omega)$ has a maximum of about $\mu_2 \approx 2300$ at around 1 MHz and this ferrite has relative large power loss.

The analytic technique for fitting of measured $\tilde{\mu}(\omega)$ spectrum follows from Eq. 6 for magnetization due to domain wall motion, if $\eta = 0, \kappa_v = 1$, *ie* for sintered ferrite.

The spectra may be traced as the combination of two loci. One fictive circular locus plotted by dashed line fits part of measured $\tilde{\mu}(\omega)$ data at higher frequencies with negative values of real components $\mu_1(\omega)$. These complex data of circular locus $\tilde{\mu}_0(\omega)$ are associated with pure resonance effects. This approximate locus can be characterised by resonance to relaxation frequency ratio $\omega_0/\omega_r > 2$. The second fictive locus plotted by pointed line corresponds to relaxation $\tilde{\mu}_r(\omega)$ component; it is subtraction $\tilde{\mu}_0(\omega)$ from measured $\tilde{\mu}(\omega)$ data. The $\tilde{\mu}_r(\omega)$ may be also fitted by Eq. 6, if $\eta = 0, \kappa_v = 1$ and $1 >> \omega/\omega_0$ with ratio $\omega_0/\omega_r >> 1$ for sintered ferrite. The rest of $\tilde{\mu}(\omega)$ data measured at frequencies $\omega < \omega_0$, *ie* below resonance frequency ω_0, are complex sum of pure resonance $\tilde{\mu}_0(\omega)$ and pure relaxation part $\tilde{\mu}_r(\omega)$.

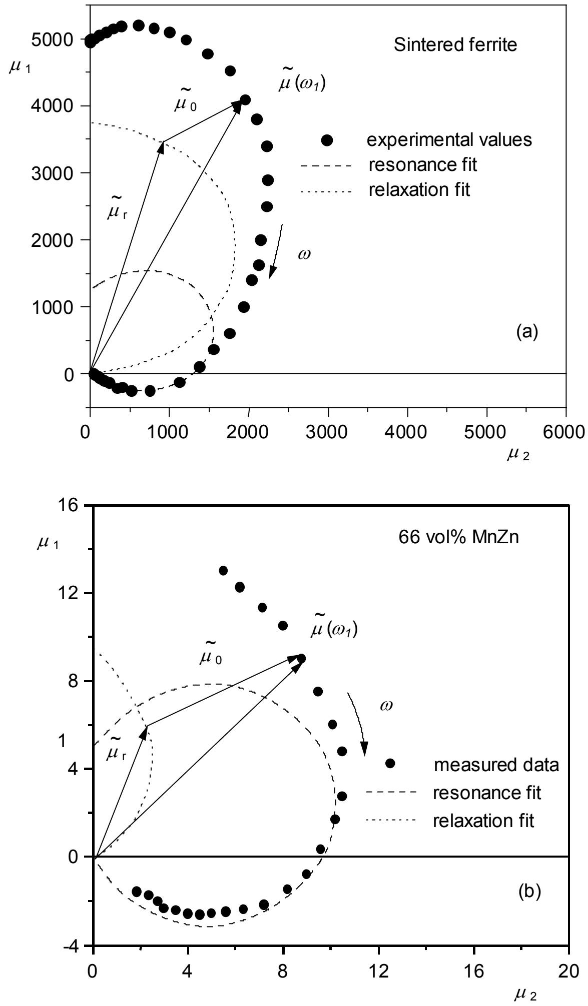

Fig. 2. The complex permeability spectra of sintered MnZn ferrite (a) and of ferrite polymer with κ_v = 66.0 vol% MnZn composite.

The frequency dependences of complex permeability $\tilde{\mu}(\omega)$ and its components $\mu_1(\omega)$ and $\mu_2(\omega)$ for the ferrite polymer composite were measured and can be described on samples, which successively contained various vol% MnZn filler powder in PVC matrix. The powder fraction of (40 - 80) µm was chosen. For the selected samples containing 66 vol% MnZn filler powder the frequency spectra of $\tilde{\mu}(\omega)$ are plotted as locus in the complex plane Fig. 2b. The locus for the magnetopolymer has the shape characteristic for the rise of resonance and in this case, the resonance frequency ratio is $\omega_0/\omega_r \cong 2$. Thus, in the composite the frequency spectra $\tilde{\mu}(\omega)$ are affected except, for relaxation effect by resonance phenomena too. The complex permeability data in Fig. 2b measured on composite samples have significantly lower $|\tilde{\mu}(\omega)|$ values than that measured on sintered ferrite sample. It is due to decreasing of ferrite volume content κ_v in magnetocomposite and as well as the demagnetising effect of ferrite particles represented by η parameter, see Eq. 1. Since the domain structure of grains in particle and also the energy of their domain walls in composite sample are influenced by demagnetising effect, then effective anisotropy field in resonance frequency $\omega_0 = \gamma H_{ef}$ is written by summation of magnetocrystalline anisotropy field $\vec{H}_a$ and the particle shape anisotropy $\vec{H}_d$, *ie* $\vec{H}_{eff} = \vec{H}_a + \vec{H}_d$. Therefore, there are prob– ably only the rotating magnetic reversals in magneto– composite. In addition the both relaxation and resonance effects of composite samples, due to shape anisotropy of small particles, rise at higher frequency region than in sintered ferrites. Thus, the demagnetising field increases with decreasing volume fraction of filler and the resonance frequency becomes higher. As a result, μ_1 can take larger value than that of the sintered ferrite in the high frequency region. The numerical fitting of the measured spectrum $\tilde{\mu}(\omega)$ of magnetopolymer composite follows from combination of Eq. 1 and Eq. 5 for magnetisation due to rotation. Each of $\tilde{\mu}(\omega)$ data in Fig. 2b can be approximated by combination of two loci, one locus having pure relaxation behaviour and second locus is a pure resonance type. The example of the superposition of the relaxation component of permeability $\tilde{\mu}_r(\omega_1)$ and the resonance $\tilde{\mu}_0(\omega_1)$ component to get $\tilde{\mu}(\omega_1) = \tilde{\mu}_r(\omega_1) + \tilde{\mu}_0(\omega_1)$ is shown in Fig. 2b for f_1 = 300 MHz.

The measured permitivity spectra $\tilde{\varepsilon}(\omega)$ of magnetocomposite samples showed preferable low ε_1 and ε_1 values and in addition $\varepsilon_1(\omega)$ data were roughly frequency independent up to 1 GHz. The frequency dependence of measured $\tilde{\varepsilon}(\omega)$ will be discussed in another paper.

4 CONCLUSIONS

We presented the short study of frequency dependence of selected electromagnetic characteristic of magneto– polymer materials. In low frequency region, both the real μ_1 and imaginary μ_2 part of composite sample are much lower than these for sintered ferrite. However, in the high frequency region, the values of μ_1 for the ferrite polymer composite are larger than for the sintered ferrite. In addition, the loss energy is more time lower in composite. Prepared ferrite polymer composite may be a promising material to serve as medium for components used under significantly higher frequencies in compared with sintered ferrites.

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