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Thermal Effects on the Ferromagnetic Resonance in Polymer Composites with Magnetic Nanoparticles Fillers

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1. Introduction

Magnetic nanopowders placed in the nonmagnetic polymer matrices become a new type of smart materials which combine mechanical properties of temperature responsive polymer matrix and magnetic response of nanoparticles. These properties are used in some biotechnological and medical applications like hyperthermia treatment, nanocolloids, magnetic nanocapsules for drug targeting, magnetic resonance imaging (MRI), intracellular manipulation etc. (e.g. (Gao & Xu, 2009; Liu et al., 2009)), in the processes of mechanical and electrical micropower generation, in nanoelectromechanical systems as MEMS/NEMS devices (e.g. (Zahn, 2001)), electromagnetic interference suppression (Wilson et al., 2004). Recently, the unusual polymer/magnetic nanoparticles systems with a negative Poisson's ratio (e.g. ferrogels Dudek & Wojciechowski (2008); Wood & Camp (2011)) have begun to be studied. They belong to the so-called auxetic materials Evans et al. (1991); Lakes (1987); Smith & Wojciechowski (2008).

Ferromagnetic resonance experiment (FMR) (Vleck, 1950) is one of the basic tools to study the magnetic properties of magnetic agglomerates in viscoelastic nonmagnetic polymer matrix. As a particular example, we consider the FMR experiment with the γ-Fe_2O_3 (maghemite) ferrimagnetic nanoparticles embedded in a multiblock poly(ether-ester) copolymer nonmagnetic matrix which has been studied both experimentally (Guskos et al., 2006; 2008) and theoretically (Dudek et al., 2010). However, the obtained results are general and applicable to other nanoparticles and other viscous materials. Note that in medical applications magnetic iron oxides are used due to their low toxicity to human. Their saturation magnetization is practically equal to the bulk value at high temperatures, with negligible coercivity and no exchange bias below the blocking temperature. These properties of the iron oxide magnetic nanoparticles suggest nearly perfect nanocrystals without significant structural disorder (Dutta et al., 2004).

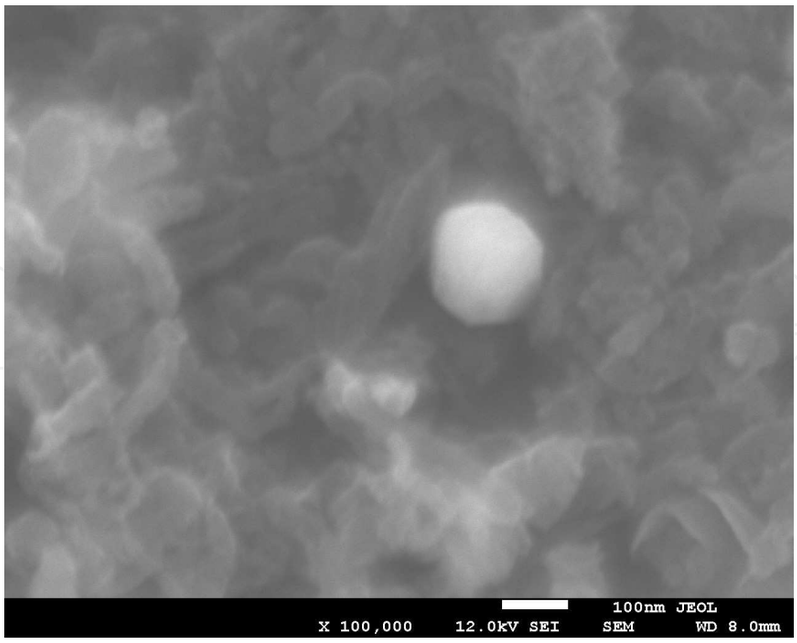

Fig. 1. SEM picture: an example of stucking a single magnetic nanoparticle in a pore - here, a carbon coated nickel nanoparticle in the porous sodium borosilicate glass.

The peculiar feature of the synthesized PEN-block-PTMO copolymer is that the magnetic fillers form agglomerates numbering from several to tens of nanoparticles. In the agglomerates the interparticle dipole - dipole magnetic interaction becomes important as well as the interaction of the magnetic nanoparticles with a non-magnetic matrix. Although the agglomerates are uniformly dispersed in the matrix their FMR spectra show additional peaks in low temperatures which originate from the orientational anisotropy of the frozen polymer blocks. The orientational dependence of the FMR spectra has been found earlier by Owens (Owens, 2003) for a colloidal suspension of γ-Fe_2O_3 nanoparticles which have been solidified in a static magnetic field (dc magnetic field). Similar observation has been found theoretically in a recent paper by Sukhov et al. (Sukhov et al., 2008). There is very instructive discussion on the shape of the ferromagnetic resonance spectra for the ensemble of the randomly distributed magnetic anisotropy axes as well as the discussion of the dependence of these spectra on temperature in terms of a stochastic model. The model is restricted to the case when the orientation of each anisotropy axis is frozen during computer simulation but it shares many features common with the experimental results, like the broadening of the FMR signal for the randomly distributed magnetic anisotropy axes as compared to the magnetic nanoparticles which all have the same orientation of the magnetic anisotropy. In paper (Dudek et al., 2008) it has been shown directly that blocking the rotational freedom of the magnetic nanoparticles, e.g. when the nanoparticles are stuck in the pores as it is suggested in Fig. 1, can produce additional resonance peaks in the FMR spectrum. In the latter case stochastic equations were used both for the magnetic nanoparticles magnetization and the rotational oscillations of the magnetic nanoparticles as a whole. The influence of the magnetic anisotropy orientation and temperature on the FMR spectra of magnetic agglomerates in polymer matrix was discussed in (Dudek et al., 2010). The most important property of the FMR spectrum depending on temperature will be discussed in the sections below.

2. Modeling ferromagnetic resonance experiment

Theoretical basis of ferromagnetic resonance can be found in the paper by van Vleck (Vleck, 1950) in which a magnetic resonance condition (Kittel's formula) for ferromagnetic materials has been derived with the help of a simple quantum model. It has been noted in the paper the importance of the effect of magnetic anisotropy on the resonance frequency. In our considerations we restrict to the case when an uniaxial anisotropy is the dominating magnetic anisotropy of the magnetic nanoparticles (Shliomis, 1975). Then, the term magnetic anisotropy axis is substituted for the easy axis of magnetization. The magnetization of magnetic nanoparticles changes after an external magnetic field is switched on and there are two mechanisms of this change: the reorientation process of magnetic nanoparticle as a whole (Brownian motion) and the Néel relaxation process of the magnetization itself. A magnetic nanoparticle, and by this the magnetic anisotropy axis, can rotate freely in a liquid carrier, but not in the case when the nanoparticle is part of a large agglomerate or its surrounding is a solid phase. The dominant interparticle interactions in the agglomerate are dipole interactions unless the nanoparticles do not form dense agglomerates where exchange interactions become important. So if we take into account the FMR experiment and we consider the agglomerate consisting of N single-domain magnetic nanoparticles, each of them experiences an effective magnetic field $\overrightarrow{H}_{\mathrm{eff,i}}$ of the form (Füzi, 2006):

$$\overrightarrow{H}_{\mathrm{eff,i}} = \overrightarrow{H}_{\mathrm{dc}} + \overrightarrow{H}_{\mathrm{ac}} + \frac{H_a}{|\overrightarrow{M}_i|}(\overrightarrow{M}_i \cdot \overrightarrow{n}_i)\,\overrightarrow{n}_i + \overrightarrow{H}_{i,\mathrm{dipole}} \tag{1}$$

where $\overrightarrow{H}_{\mathrm{dc}}$ is the external direct current (dc) magnetic field, $\overrightarrow{H}_{\mathrm{ac}} = \overrightarrow{H}^0_{\mathrm{ac}}\cos(2\pi f t)$ is the external alternating current (ac) magnetic field of frequency f, $\overrightarrow{H}_{i,\mathrm{dipole}}$ represents dipolar magnetic field produced by the magnetic nanoparticles of the agglomerate

$$\overrightarrow{H}_{i,\mathrm{dipole}} = -\frac{1}{4\pi}\sum_{j=1,j\neq i}^{N}\left(\frac{\overrightarrow{M}_j}{r_{ij}^3} - 3\frac{(\overrightarrow{M}_j\cdot\overrightarrow{r}_{ji})\,\overrightarrow{r}_{ji}}{r_{ji}^5}\right), \tag{2}$$

$\overrightarrow{M}_i$ denotes magnetization of the nanoparticle i ($M = M_s V$ for the nanoparticle of volume V and saturation magnetization M_s), r_{ij} is the distance between nanoparticles i and j, H_a represents the magnetic anisotropy field which is defined as

$$H_a = \frac{2K_a}{\mu_0 M_s} \tag{3}$$

where K_a is magnetic anisotropy constant, and μ_0 is constant of permeability. The symbol $\overrightarrow{n}_i$ in Eq. (1) is a unit vector along the magnetic anisotropy direction of the nanoparticle i with the components

$$n_{x,i} = \sin(\varphi_i)\cos(\theta_i), \tag{4}$$
$$n_{y,i} = \sin(\varphi_i)\sin(\theta_i), \tag{5}$$
$$n_{z,i} = \cos(\varphi_i). \tag{6}$$

and φ_i and θ_i are the angles vector $\overrightarrow{n}_i$ makes with the z-axis and x-axis, respectively.

A rotating external magnetic field $\overrightarrow{H}_{\mathrm{ac}}$ is transverse to $\overrightarrow{H}_{\mathrm{dc}}$. We assume that the external dc magnetic field is oriented in the z-direction and the external ac magnetic field in the x-direction (Jung et al., 2002). Then, for the effective magnetic field defined in Eq. (1) the ferromagnetic resonance condition can be expressed as follows:

$$f = \frac{\gamma}{2\pi} H_{\mathrm{eff}} \tag{7}$$

where $\gamma = 2.21 \times 10^5 s^{-1}(A/m)^{-1}$ denotes the gyromagnetic ratio. In practice, the spectrometers EPR/FMR are built for one value of frequency f and then the dc magnetic field becomes a parameter to be changed to get the resonance condition. In our case the ac magnetic field frequency $f = 9.37$ GHz. Note that even in the case of a single magnetic nanoparticle (N=1) its resonance frequency strongly depends on the orientation of the magnetic anisotropy axis with respect to the dc magnetic field direction.

It turns out that the magnetic nanoparticle's magnetization dynamics can be modeled with the help of the classical spin model which represents stochastic version of the Landau-Lifshitz equation ((Gilbert, 1955; Landau & Lifshitz, 1953)) :

$$\frac{d\overrightarrow{M}_i}{dt} = -\gamma \overrightarrow{M}_i \times [\overrightarrow{H}_{\mathrm{eff,i}} + \overrightarrow{B}_i] - \alpha \frac{\gamma}{M_s V} \overrightarrow{M}_i \times (\overrightarrow{M}_i \times [\overrightarrow{H}_{\mathrm{eff,i}} + \overrightarrow{B}_i]), \tag{8}$$

where $i = 1, 2, \ldots, N$, and α denotes the damping constant. The symbol $\overrightarrow{B}_i$ represents the white-noise field fluctuations (e.g. (Jönsson, 2003), (Usadel, 2006)). Then the thermal averages of $\overrightarrow{B}_i = (B_{x,i}, B_{y,i}, B_{z,i})$ fulfill the relations:

$$\langle B_{q,i}(t) \rangle = 0, \;\; q = x, y, z, \tag{9}$$

$$\langle B_{q,i}(t) B_{p,i}(t') \rangle = \frac{2\alpha k_B T}{\gamma M_s V} \delta_{q,p} \delta(t - t'), \;\; p = x, y, z. \tag{10}$$

The magnetic properties of the magnetic nanoparticles can be described with the help of the solutions $\overrightarrow{M}_i(t)$ of this set of equations.They strongly depend on the magnetic anisotropy axis orientation. In particular, the shape of the magnetic hysteresis loop can change from the almost square like to the case when it vanishes depending on the orientation of the external dc magnetic field with respect to the orientation of the magnetic anisotropy axis. This can be seen in Fig. 2 and Fig. 3 in which the magnetic hysteresis loops are presented for the z-component of the nanoparticle's magnetization in the case when the anisotropy axis orientation oscillations are close to the z-direction (parallel to dc magnetic field) and close to the x-direction (transverse to dc magnetic field), respectively. The hysteresis loops, which are shown in the figures, result from the computer simulation of a simplified model of a carbon coated magnetic nanoparticle where the coating is represented by C_{60} molecule. In the model, the magnetic nanoparticle is represented by magnetic anisotropy axis and its magnetization follows the Landau-Lifshitz equation (Eq. (8)). The carbon atoms in C_{60} molecule vibrate according to the molecular dynamics method. The rotational oscillations of a fullerene (and by this the magnetic anisotropy axis rotations) are harmonically bonded to the z-direction and x-direction, respectively, with a given spring constant. The latter means that the magnetic nanoparticle cannot rotate freely. The larger temperature is the larger the rotational oscillations are. Besides the spring force the anisotropy axis experiences the

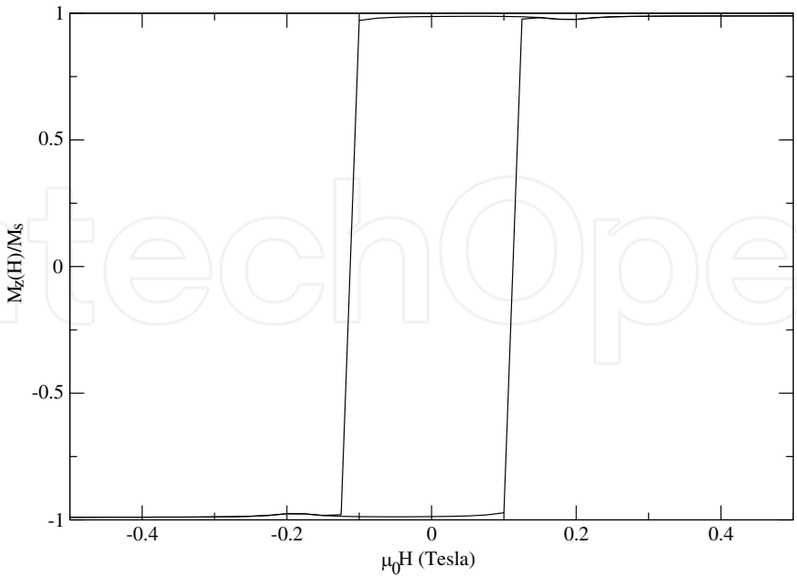

Fig. 2. Magnetic hysteresis loop of the z-component of the magnetic nanoparticle's magnetization in the case when the orientation of the magnetic anisotropy axis undergoes the small oscillations around the z-direction (parallel to the external dc magnetic field). Some parameters of the computer simulation: demagnetizing factor in shape anisotropy $D = 0.15$ ($K_a = \mu_0(1-3D)M_s^2/4$), $\alpha = 0.066$, $R = 2$nm, $M_s = 450kA/m$, T=10K.

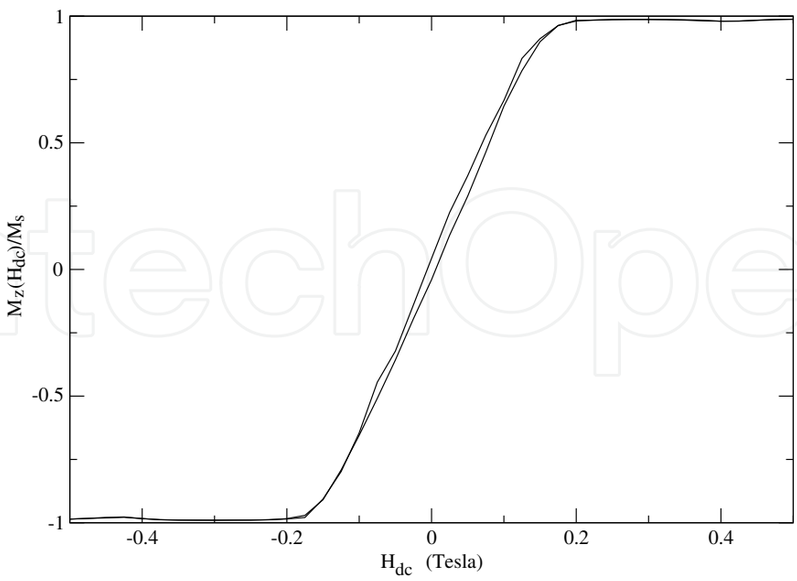

Fig. 3. The same as in Fig. 2 but the magnetic anisotropy axis orientation oscillates around the x-direction (transverse to the external dc magnetic field).

magnetic torque which is represented by two opposite point forces (Dudek et al., 2010) applied to the anisotropy axis with the strength

$$| \overrightarrow{F} | = \frac{1}{R} | K_a V \sin(2\Psi) | \tag{11}$$

where R is the fullerene's radius, and the greater the angle Ψ between the easy axis, represented by vector $\overrightarrow{n}$, and magnetization $\overrightarrow{M}$, the greater the magnetic torque. The model of the magnetic nanoparticles used in the computer simulations has been shown in Fig. 4 in the case when the magnetic anisotropy axis is, respectively, parallel and perpendicular to the external dc magnetic field.

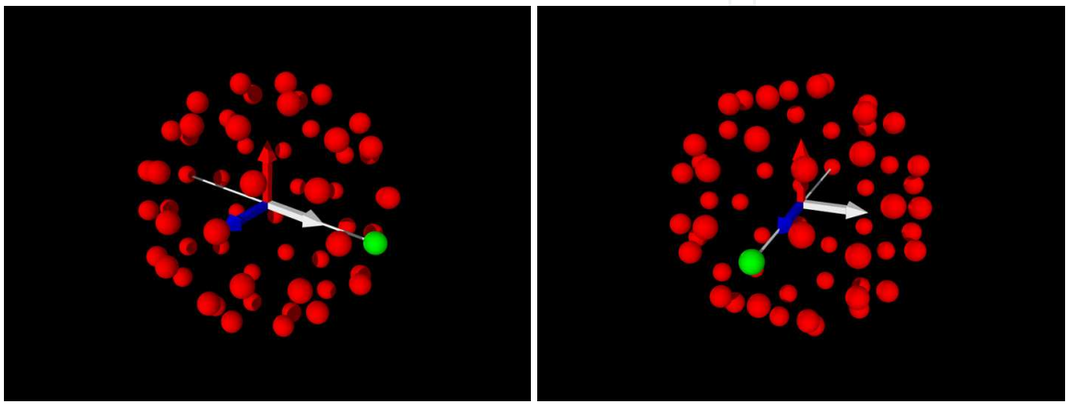

Fig. 4. Model of carbon coated magnetic nanoparticle in the case when the coating is represented by C_{60} molecule. The magnetic nanoparticle is represented by the anisotropy axis which, in the model, passes through the center of the fulleren and the carbon atom painted green, in the figure. The magnetic nanoparticle was not drawn with clarity reasons. The cartesian coordinate system has been plotted and the blue axis represents the z-direction which is the direction of the external dc magnetic field and the white axis represents the x-direction.

The same features of the magnetic hysteresis loops as those presented in Fig. 2 and Fig. 3 can be observed in magnetic nanowires, e.g. (Sorop et al., 2004), where the similar relationship between the shape anisotropy of a nanowire and the external dc magnetic is observed. In low temperatures, much below 100K, the large agglomerates of the γ-Fe_2O_3 (maghemite) ferrimagnetic nanoparticles embedded in a multiblock poly(ether-ester) copolymer nonmagnetic matrix Guskos et al. (2006; 2008) are practically frozen into the matrix with a random orientation of the magnetic anisotropy axes. Then, the observed magnetic hysteresis loop represents the averaged one which is approximately a mixture of the cases discussed in Fig. 2 and Fig. 3. It is worth to add that in high temperatures, where the block copolymer is dissolved, the magnetic properties resemble the properties of ferrofluids and there is no observed magnetic hysteresis loop.

Much more information on the magnetic properties of the polymers filled with nanoparticles can be get from the analyses of the absorption lines in FMR experiment. They can be represented by the imaginary part of the dynamic magnetic susceptibility

$$\chi = \chi' - i\chi'', \tag{12}$$

where χ'' denotes total hysteresis losses per volume of magnetic nanoparticle through a cycle of the magnetization. For the chosen magnetic fields $H_z = H_{dc}$ and $H_x = H_{ac}$ the components of the complex ac susceptibility (Eq. (12)) can be calculated by performing the Fourier transform on the time averaged x-component of the magnetization, i.e.,

$$\chi = \frac{1}{\tau H_{\mathrm{ac}}^0} \int_0^\tau dt M_x(t) e^{-i2\pi f t}, \tag{13}$$

where $\tau = 1/f$. In the case of theoretical modeling , the values $M_x(t)$ can be obtained from the Landau-Lifshitz equation (Eq. 8). In real FMR experiments, the absorption lines derivatives, $d\chi''/dH_{\mathrm{dc}}$ (the derivative of the out-of-phase susceptibility) are measured instead of direct measuring χ''. In Fig. 5 there are presented the absorption lines derivatives obtained for the

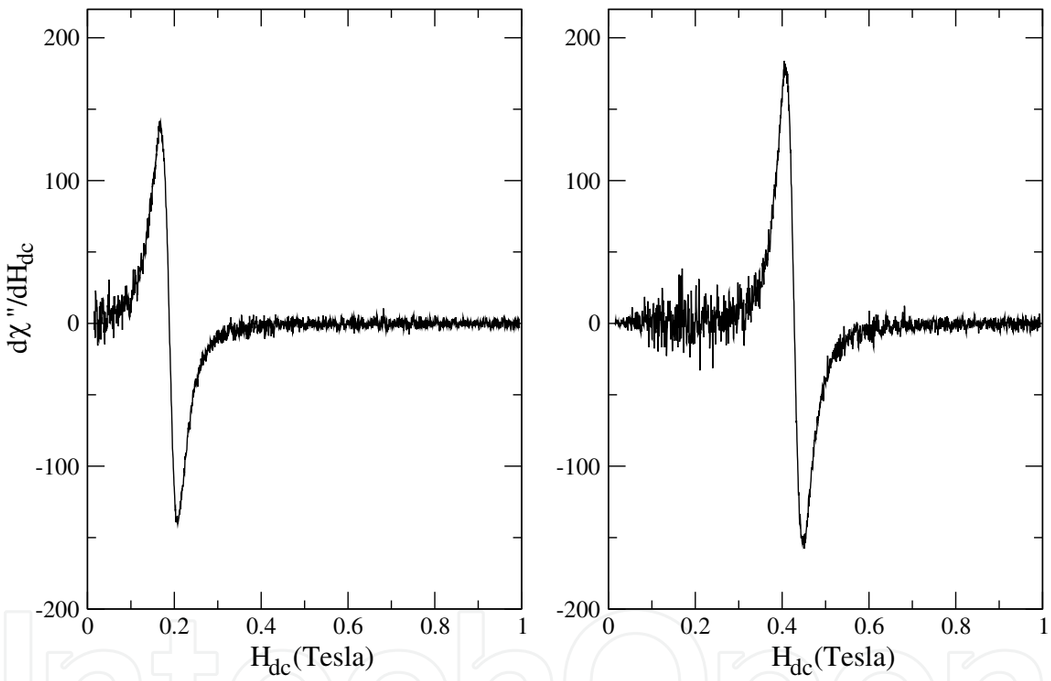

Fig. 5. Absorption lines derivatives, $d\chi''/dH_{\mathrm{dc}}$ resulting from the computer simulations in the case when the magnetic anisotropy axis orientation oscillates around the direction parallel and transverse to the external dc magnetic field. The parameters of the computer simulation are the same as in Fig. 2.

model of the carbon coated nanoparticles shown in Fig. 4 in the case when their magnetic anisotropy axis oscillations are controlled by the harmonic forces applied to the ends of the axis and the forces are coupled with the z-direcion and x-direction, respectively. Note that if the magnetic anisotropy axis is linked to the direction which is tranverse to the direction of H_{dc} then the corresponding resonance magnetic field H_r becomes shifted to higher values of H_{dc} compared with the case when it is linked to the direction which is parallel. At the value of $H_{\mathrm{dc}} = H_r$ the dynamic susceptibility χ'' takes its maximum value. It is worth emphasizing that the energy absorbed by the magnetic nanoparticles from the external AC magnetic field

is proportional to χ''. After the energy is converted into heat there is observed an increase ΔT of temperature which can be estimated at each cycle of the applied AC magnetic field with a given frequency $\omega = 2\pi f$ as follows (Sellmyer & Skomski, 2006):

$$\Delta T = \frac{\mu_0 V H_0^2}{c\, m_{\text{ferro}}} f \chi'' \tag{14}$$

where c is the average specific heat of carbon and magnetic nanoparticle $c = (c_{\text{carbon}} + c_{\text{ferro}})/2$, m_{ferro} represents mass of magnetic nanoparticle. The remote heating of the magnetic nanoparticles can be important in viscous materials in low temperatures for reorientation processes among the magnetic nanoparticles. This particular feature of the magnetic nanoparticles to posses the different values of H_r for different orientations of their magnetic anisotropy axis (Fig. 5) becomes another interesting property of materials filled with magnetic nanoparticles where the static magnetic field H_{dc} can be used as a remote switcher for the local heating different groups of nanoparticles.

3. Temperature dependence of the spectral lines in viscous magnetic materials

In the case when the magnetic nanoparticles are placed in a viscous material for which the viscosity varies significantly depending on temperature, magnetic properties of such materials are also beginning to significantly depend on temperature. This special property of viscous magnetic materials has been studied experimentally for maghemite nanoparticles embedded in a multiblock poly(ether-ester) copolymer nonmagnetic matrix Guskos et al. (2006; 2008). The experiments were performed in a wide range of temperatures, 3.5-288 K. In addition to the experimental results were also carried out theoretical studies Dudek et al. (2010). Several examples of spectral lines discussed in Dudek et al. (2010) are presented in Fig. 6 for concetration of 0.1% of γ-Fe_2O_3 nanoparticles dispersed in the polymer matrix. The figure shows the completely different FMR spectra in the range of low temperatures and high temperatures. These two ranges of temperatures are also evident in the resonance field H_r (Fig. 7) as a function of temperature, where at low temperatures a marked decrement of H_r is observed. In the latter case the experimental results for two different concentrations of magnetic nanoparticles are presented and up to 50 K there is no signicant difference between them. This could mean that the thermal properties of non-magnetic matrix, in this case of a multiblock poly(ether-ester) copolymer, are of decisive importance for the magnetic properties of the magnetic agglomerates and not the reorientation processes between magnetic nanoparticles.

In low temperature region we have solid-like nonmagnetic matrix where magnetic relaxation takes place through the process of magnetization relaxation (Neél relaxation). Once the magnetic anisotropy axes are oriented randomly some additional peaks appear on the spectral lines at the higher values of H_{dc}. This property of spectral lines is shown in the previous section on the example of a single magnetic nanoparticle. The presence of many magnetic agglomerates consisting of different numbers of magnetic nanoparticles is one of the mechanisms for observing the broadening of the spectral lines. At higher temperatures the magnetic relaxation takes place both through the magnetization relaxation and rotation of the whole nanoparticle in a nonmagnetic surrounding and the additional peaks observed on spectral lines at low temepratures do vanish.

A simplified theoretical model was constructed in (Dudek et al., 2010) where a cluster consisting of N magnetic nanograins is placed randomly into a non-magnetic polymer matrix.

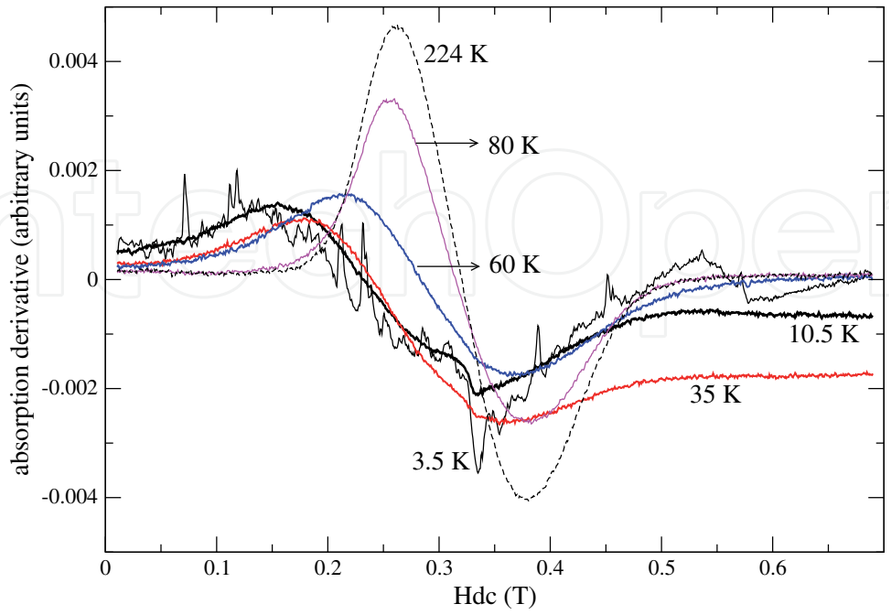

Fig. 6. The temperature dependence of $d\chi''/dH_{dc}$ for 0.1% γ-Fe_2O_3 dispersed in PEN-block-PTMO matrix.

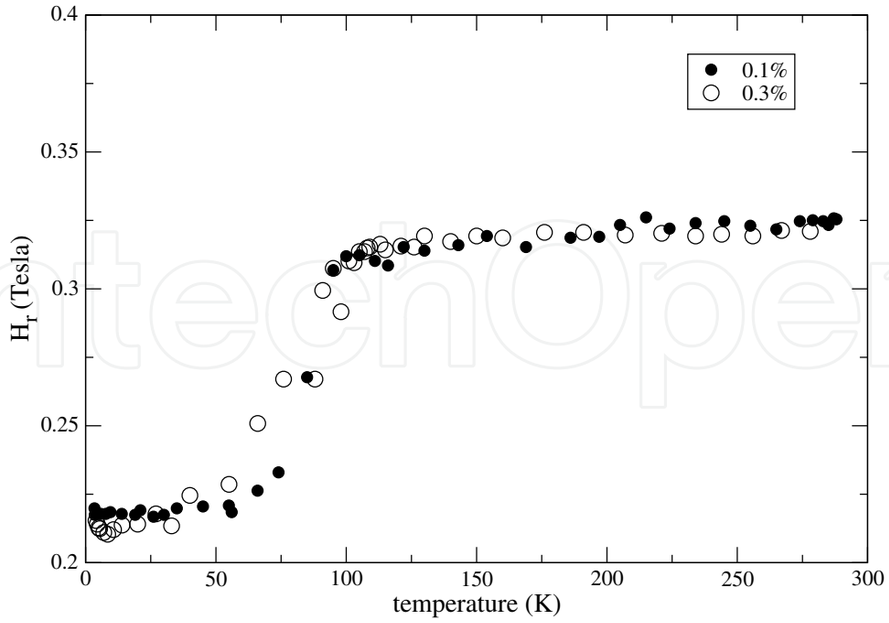

Fig. 7. An example of the dependence of the resonance field H_r on temperature for magnetic nanoparticles γ-Fe_2O_3 in PEN-block-PTMO matrix. The plots correspond to two concentrations of nanoparticles of 0.1% and 0.3%.

They occupy a permanent position but may rotate. Each of the magnetic nanograins $i = 1, 2, \ldots, N$ has magnetization M_i which dynamics is described with the help of the stochastic version of the Landau-Lifshitz equation in Eq. (8). The rotational dynamics of magnetic nanoparticles is described with the help of the Langevin equations for the magnetic anisotropy axis orientation. These equations take the following form (Dudek et al., 2010; 2008):

$$\frac{d\varphi_i}{dt} = -\frac{2}{R\,\xi}\,|K_a V \sin(2\psi_i)|\,\sin(\varphi_i - \varphi_i') - \frac{K_{\mathrm{el}}}{\xi}\sin(\varphi_i - \varphi_{0,i}) + \frac{1}{\xi}\lambda_{\varphi_i}, \tag{15}$$

$$\frac{d\theta_i}{dt} = -\frac{2}{R\,\xi}\,|K_a V \sin(2\psi_i)|\,\sin(\theta_i - \theta_i') - \frac{K_{\mathrm{el}}}{\xi} sin(\theta_i - \theta_{0,i}) + \frac{1}{\xi}\lambda_{\theta_i}. \tag{16}$$

in the diffusion limit, where ξ represents the friction of the i-th nanoparticle in the elastic non-magnetic polymer matrix and $\lambda_{\varphi,i}$ and $\lambda_{\theta,i}$ represent the white-noise driving torque (Coffey et al., 1984; Gardiner, 1983) for i-th nanoparticle, and K_{el} represents the spring constant which controls the rotational oscillations of the magnetic anisotropy axis. In the above stochastic equations the thermal rotational fluctuations of the i-th magnetic nanoparticle are characterized by temperature T and λ_{φ_i} and λ_{θ_i} and they fulfill the relations:

$$\langle \lambda_q(t) \rangle = 0 \tag{17}$$

$$\langle \lambda_q(t)\lambda_{q'}(t') \rangle = 2k_B T\xi\delta(t - t'), \tag{18}$$

where $q = \varphi_i, \theta_i$. The angles φ' and θ' represent the angles which the magnetization $\overrightarrow{M}$ makes with z-axis and x-axis, and the angles φ_0 and θ_0 are the initial angles of the easy axis after the magnetic nanoparticle has been built into polymer matrix. The numerical scheme applied to the stochastic equations in (Dudek et al., 2010) is the Euler-Maruyama method. The theoretical model introduced in (Dudek et al., 2010) reproduces qualitatively the results of the experiment (Guskos et al., 2006; 2008). In particular, the FMR spectrum and the dependence of H_r on temperature have qualitatively the same properties. It is evident from Fig. 8 and Fig. 9 if we compare them with Fig. 6 and Fig. 7.

The results of the theoretical model have been obtained by two assumptions. The first one is assuming an empirical model for the viscosity parameter ν, the Arrhenius law,

$$\nu(T) = \nu_0 \mathrm{e}^{\mathrm{E/k_B T}} \tag{19}$$

where E is the activation energy. In the model, the viscosity parameter $\nu(T)$ is related to the rotational friction parameter ξ of magnetic nanoparticles in a polymer surounding (used in Eqs. (15) and (16)), as follows:

$$\xi = 8\pi\nu(T)r^3, \tag{20}$$

where $r = R/2$ denotes the radius of a sphere representing magnetic nanoparticle and its polymer coating. Hence the simple assumption in Eq. (19) and not the presence of a phase transition is responsible for the qualitatively different behavior of H_r in the low and high temperatures in the theoretical model (Fig. 9).

The second assumption is introducing the Bloch law approximation

$$M_s(T) = M_0(0)\left(1 - \left(\frac{T}{T_0}\right)^{\delta}\right) \tag{21}$$

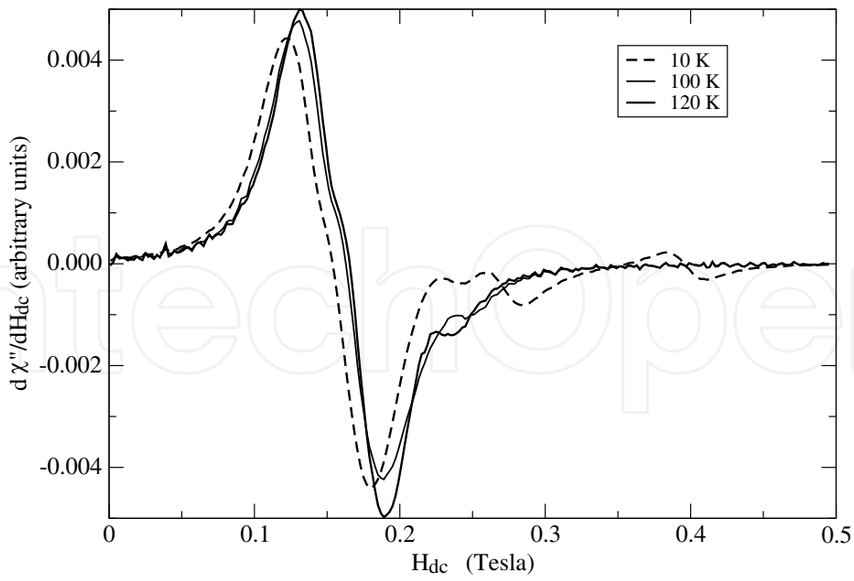

Fig. 8. Computer simulations of the temperature dependence of $d\chi''/dH_{\mathrm{dc}}$ calculated for N=30 magnetic nanoparticles in the case when their magnetic anisotropy axes are randomly oriented (Dudek et al., 2010). The parameters of the computer simulation are the same as in Fig. 2.

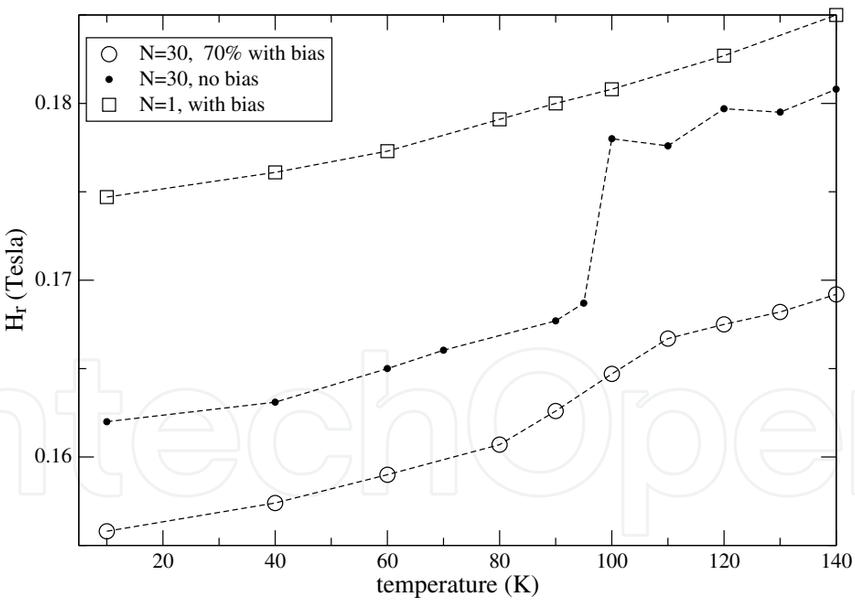

Fig. 9. Computer simulations of the dependence of the resonance field H_r on temperature for agglomerates of magnetic nanoparticles (Dudek et al., 2010). The agglomerates consisting of $N = 30$ magnetic nanoparticles represent two cases: when all magnetic nanoparticles are randomly oriented and when 70% of them is aligned with the dc magnetic field. In the case of a single magnetic nanoparticle (N=1) its magnetic anisotropy axis is aligned with the dc magnetic field.

for the magnetization of the magnetic nanoparticles where T is temperature, $\delta = 1/3$ and T_0 is some constant. The value of α is a parameter of the model under consideration. Another value of α can be also found in publications on magnetic materials.

The complexity of the FMR spectral lines can be seen in the example in Fig. 10 where the absorption lines derivatives $d\chi''/dH_{\mathrm{dc}}$ have been plotted for a single magnetic nanoparticle in the case when its easy magnetic axis oscillates around the direction perpendicular to the external dc magnetic field in a surrounding with temperature-dependent viscosity $\nu(T)$. In low temperatures the magnetic resonance field H_r moves towards the lower values of H_{dc} with increasing temperature instead to move towards the higher values of H_{dc} as it is in the case of magnetic nanoparticles oscillating around the direction of the dc magnetic field. Only above a certain temperature there is no qualitative difference in the FMR spectrum for magnetic nanoparticles with magnetic easy axis oriented parallel or perpendicular to the external dc magnetic field.

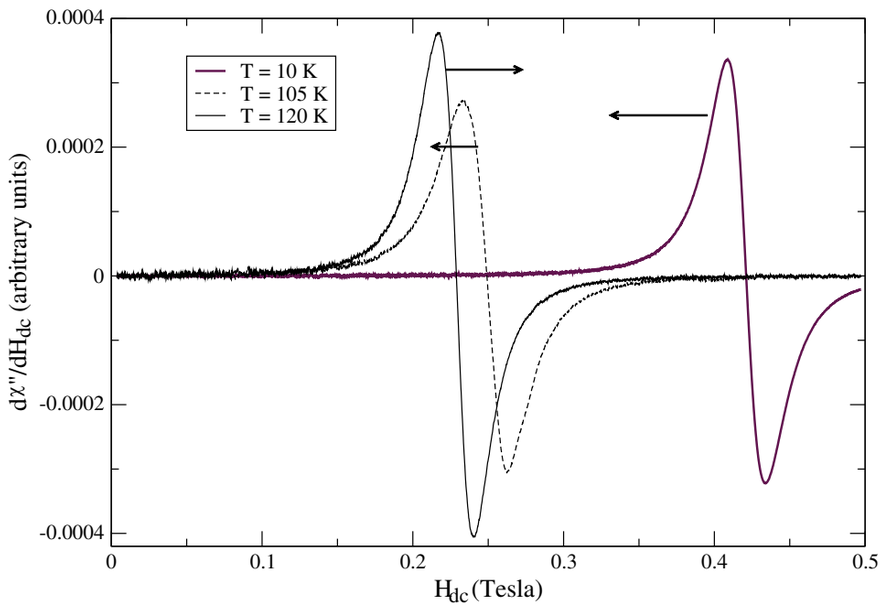

Fig. 10. Absorption lines derivatives, $d\chi''/dH_{\mathrm{dc}}$ in theoretical model (Dudek et al., 2010) for a single ($N = 1$) magnetic nanograin in the case when its magnetic anisotropy axis oscillates around the direction transverse to the direction of the external dc magnetic field. The plotted curves correspond to temperatures $T = 10, 105, 120K$, respectively. In low temperatures the magnetic resonance field H_r moves towards the lower values of H_{dc} with increasing temperature and only above a certain temperature it begins to move toward the higher values of H_{dc}.

In the case of magnetic agglomerates dispersed in a viscous medium and which consist of a large number of magnetic nanoparticles with randomly oriented axes relative to the field H_{dc} the mechanism shown in Fig. 10 can be important in low temperatures.

4. Conclusions

Both the discussion in section 2 and FMR spectrum in Fig. 5 show that the static magnetic field H_{dc} can be used as a remote switcher for the local heating different groups of nanoparticles

corresponding to different orientations of their magnetic easy axis. This property of the dependence of a maximum of χ'' on the orientation of the magnetic anisotropy axis with respect to the external dc magnetic field may be useful in designing new materials such as multi-functional magnetic nanocapsules. The thermal effects on the FMR spectrum in polymer composites filled with magnetic nanoparticles provide additional information about the magnetic structure of the material.

5. Acknowledgments

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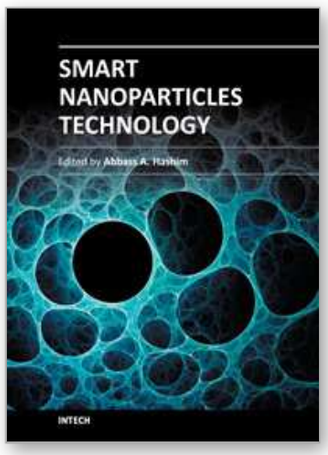

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In the last few years, Nanoparticles and their applications dramatically diverted science in the direction of brand new philosophy. The properties of many conventional materials changed when formed from nanoparticles. Nanoparticles have a greater surface area per weight than larger particles which causes them to be more reactive and effective than other molecules. In this book, we (InTech publisher, editor and authors) have invested a lot of effort to include 25 most advanced technology chapters. The book is organised into three well-heeled parts. We would like to invite all Nanotechnology scientists to read and share the knowledge and contents of this book.

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