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AN INVESTIGATION ON HIGH FREQUENCY PERMEABILITY OF POLYCRYSTALLINE FERRITES

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Abstract. *The problem under examination is the magnetic loss of polycrystalline ferrites. Their total loss include: hysteresis, eddy current and anomalous (AN) or excess ones. The mentioned first two losses more or less adequately are covered by modified Steinmetz equation whereas AN loss is less well understood. Conceptually this loss is defined by the components of complex permeability spectra of ferrites which as a rule are experimentally obtained. Large body of these experimental spectra shows a great variety of forms and specific features. This variety is the main reason why there still is not adequate analytic presentation of AN loss. It is shown in the research that important progress is possible to achieve in analytic presentation of AN loss on the basis of realistic account of microstructure of polycrystalline ferrites and dividing the variety of all samples into subgroups according to their actual structure.*

Keywords: *polycrystalline ferrite, complex initial permeability, magnetic spectra, microstructure.*

Introduction

Polycrystalline soft ferrites (PF) as the most significant magnetic materials for electronics find use in numerous of its high frequency application fields: in electromagnetic compatibility (EMC) domain as energy absorbing materials and filtering magnetic elements; in switch-mode power supply systems as energy storing and filtering components; within broad range of different inductive elements as magnetic flux concentrators, in the new class of composite materials – metamaterials as an active constituent, a.o. No matter what is actual application of PF, the user essentially needs to know, along with the set of other appropriate their characteristics, the magnetic loss parameters as well (the desired level of the losses may be quite different in different applications: usually as high as possible for the above mentioned EMC; typically as low as possible for energy storage and inductive elements). Total magnetic loss of magnetic materials conventionally (nevertheless with certain degree of scepticism because lack of theoretical justification [2]) is presented by three components [1]: hysteresis, classical eddy current and anomalous (excess, residual) loss. Such a decomposition attempts to underline the main reasons of magnetic loss but research activities on this ground does not bring to proper analytic presentation of the components still (especially anomalous one); as a consequence there appear new and new pertinent publications and improved and modified loss models. At this situation in practice the presentation of total loss both of metallic and ferrite magnetics rather often is based on well known Steinmetz empirical equation:

$$P_{core} = k\, f^{a} B_m^{b}, \tag{1}$$

where P_{core} is the magnetic core average power dissipation per unit volume; k, a, b are the material dependent empirical coefficients determined by best-fitting of measured data, f is the sinusoidal operation frequency and B_m is the peak value of magnetic flux density (the induction); for ferrites a is between *1.1…1.9* and b is in the range *1.6…3* [3]. Manufactures of magnetic materials typically make known these empirical coefficients or display the experimental curves of P_{core} over limited ranges of frequency and flux density [4]. In the case of nonsinusoidal magnetization there is offered, e.g., modified Steinmetz equation [2].

Even so, such empirical presentation is a highly limited way of looking at the loss since Eq.1 accounts only for influence of two parameters – f and B therein limited ranges of their values, but ignores several other important factors, e.g., type of magnetization process (domain wall displacement or spin rotation), influence of microstructure characteristics, a.o. This is why magnetic loss problems still are challenging; the solutions of problems are being searched by a closer look into generalization [6] as well as more adequate separation of total loss in components [7] both within the frequency and the time domains [5].

This study deals with the anomalous loss problems of PF, which there are studied on the basis of the concept of relative complex permeability:

$$\mu_r^*(f) = \mu'(f) - j\mu''(f), \tag{2}$$

where $\mu'(f)$ is the real and $\mu''(f)$ is the imaginary parts of a complex permeability $\mu^*(f)$ at the frequency f (it is common also to name $\mu'(f)$ and $\mu''(f)$ as the dispersion (DCp) and the absorption (ACp) components of magnetic spectrum (MS) respectively). This concept is the most appropriate for practically nonconducting materials such as PF [8]: there is possible to ignore macroscopic eddy currents and in the case of weak excitation fields the hysteresis loss as well. This in fact means that there really is investigated anomalous loss (at times named as resonance/relaxation loss [9]), corresponding to complex *initial* permeability (CIP), $\mu_{ri}^*(f)$; from here on Eq.2 is used in this sense omitting as a rule the subscript *i*. Use of CIP approach to anomalous loss allows more directly to account for influence of microstructure parameters of PF on its loss characteristics.

Losses versus magnetic spectra

The presentation of magnetic loss by CIP in fact implies that DCp and ACp of spectrum are known over proper frequency range. The loss most directly is proportional to ACp $\mu''(f)$ but the real practice calls for DCp $\mu'(f)$ as well since important loss characteristic – loss tangent $\tan\delta(f)$ is defined as

$$\tan\delta(f) = \mu''(f)/\mu'(f) \tag{3}$$

which in its turn is possible immediately to relate with the specific loss [10]:

$$p(f) = \left(\tan\delta(f)/\mu_a\right)\pi f B^2, \tag{4}$$

where p is the loss per unit volume; μ_a is the absolute permeability, $\mu_a = \mu'(f)\cdot\mu_0$, $\mu_0 = 4\pi\cdot 10^{-7}\ H/m$; B is the effective value of induction (flux density). From Eqs.(3) and (4) it gets clear that the deeper insight into magnetic loss of PF calls for investigation of CIP components behaviour in frequency range (typically within radiofrequencies) and for their proper analytic presentation.

The problem of analytic presentation of CIP spectra appears concurrently with the publication of the first research on absorption and dispersion in PF [11]. Then there comes a time with active investigations on MS and soon the achievements were summarized in the reviews [12, 13] showing the manner in which various researchers first of all were trying to find out the dominating magnetization process of PF using often the graphical forms of experimental MS as an argument as well. A clear understanding of magnetization process is crucial for CIP spectra modeling. The problem seems to be solved at previous seventies and eighties (mainly by investigations inspired by basic works of A.Globus, e.g. [14]) when it was stated that CIP definitely depend on microstructure characteristics (more pronouncedly on average grain size D_a) and that dominating magnetization mechanism is domain wall (DW) displacement.

At times however there appear claims that the dominating magnetization process is the spin rotation [15]. We presume that MS data taken over really broad frequency range strongly suggest that the highest losses (related with the most pronounced absorption and dispersion) is connected with DW processes. In more details it is substantiated by details in Fig.1

(experimental data are taken from [16]) which shows that if one moves across MS in general there can be found three dispersion regions [16]: a) in *kHz* range – relaxation type diffusion after effect (DIF), not always presented; b) in the decades placed directly near *1MHz* – the large amplitude dispersion attributed to DW processes; c) in the decade of several *100MHz* – the small amplitude dispersion related to the natural spin resonance (NSR).

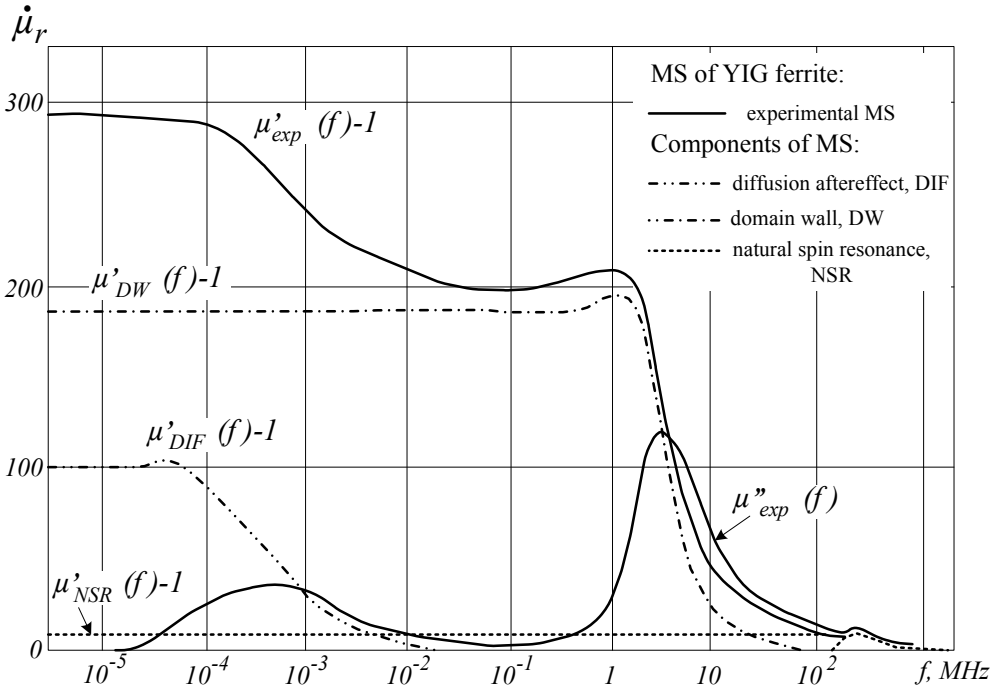

Fig.1. **Results of MS decomposition: the experimental ACp $\mu''_{\exp}(f)$ firstly is graphically broken in three clearly seen absorption components, which consecutively are used for calculation of corresponding components of DCp $\mu''_{DW}(f)$, $\mu''_{DIF}(f)$, $\mu''_{NSR}(f)$ by KK relations**

This becomes clearer after decomposition of ACp $\mu''_{\exp}(f)$ into three mentioned components [17] and calculation of DCp $\mu'(f)$ by the use of Kramers-Kronig (KK) relations:

$$\mu'(f)-1=\frac{2}{\pi}\int_0^\infty \frac{x\mu''(x)}{x^2-f^2}dx;\ \mu''(f)=-\frac{2}{\pi}f\int_0^\infty \frac{\mu'(x)-1}{x^2-f^2}dx\ . \qquad (5)$$

Within the radiofrequency range (at room temperatures) for spinel and garnet type PF (most often used in practice) typically more or less clear are observed DW and NSR dispersion regions. Similarly as in Fig.1 contribution from NSR process in the total permeability $\mu^*(f)$ of a sample often is small and frequency independent up to very high frequencies; this is why the modeling of CIP is restricted over the region of large amplitude dispersion as DW processes.

Approach to MS based on account of their characteristic features

When displayed as graphical curves the experimental MS disclose great variety of forms thus sending one first of all in search of most important typical characteristics of the spectra (it is apt at this point to mention that it is meaningless to analyze doubtful experimental spectra – e.g., the ones not obeying KK relations, Eq.5, at least).

The typical experimental ACp of MS (Fig.2) is asymmetrical along $\log f$ scale axis and broadband (often extending over several decades of f [13]) thus far in excess broader than it is obtainable by the approximation with the simple relaxation (with one relaxation time) dependence:

$$\mu'(f) = \mu_{stat} / [1 + (\tau f)^2] \; ; \quad \mu''(f) = \mu_{stat} \tau f / [1 + (\tau f)^2], \tag{6}$$

where μ_{stat} is the static value of CIP. But even with this fact that dispersion within MS is pronouncedly broad, a closer look at DCp reveals the clear evidence of resonance attributes as well (positive ups on DCp and negative downs on ACp): in Fig.1 near *1MHz* and in Fig.2 near *2MHz* and *1GHz*. If the approximation of MS is done by the use of simple harmonic oscillator relations:

$$\begin{aligned} \mu'(f) &= \mu_{stat} f_0^2 (f_0^2 - f^2) / [(f_0^2 - f^2)^2 + 4\xi^2 f_0^2 f^2], \\ \mu''(f) &= 2\mu_{stat} \xi f f_0^3 / [(f_0^2 - f^2)^2 + 4\xi^2 f_0^2 f^2], \end{aligned} \tag{7}$$

with ξ as the normalized damping *const*, then in the case of $\xi < 0.5$ the resonance features is possible to reproduce, but in the substantially closer frequency limits corresponding to much narrower width of ACp (between the ascending and the descending parts of absorption).

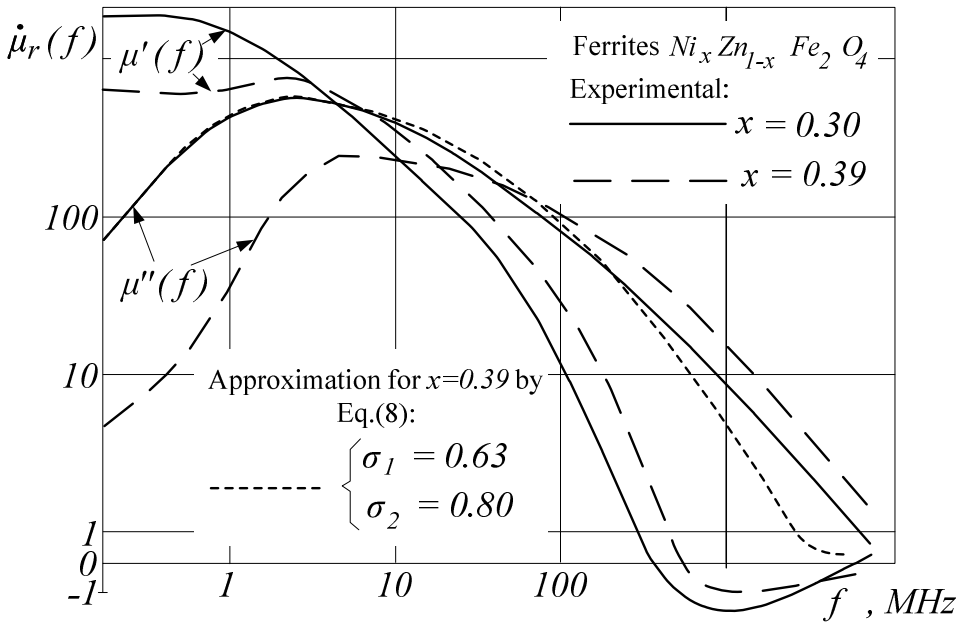

Fig.2. **Experimental MS of NiZn polycrystalline ferrites showing as it usually is an available compromise of both relaxation and resonance features**

Inadequate presentation of MS separately by the relaxation and the resonance dependences (but at the same time with several features of reality) naturally calls for their superposition, i.e., joint use of Eqs. (6) and (7) (in fact proposed by Y.Naito [18]). In this case it is assumed that for frequency $f \to 0$ static permeability

$$\mu_{stat} = \mu_{stat/relax} + \mu_{stat/reson}$$

i.e., is divided into relaxation, $\mu_{stat/relax}$ and resonance, $\mu_{stat/reson}$ components which are used with their frequency dependences according to Eq.6 and Eq.7 correspondingly. Even though there is no physical background for this decomposition of μ_{stat} as well as of parameter τ, ξ, f_0 estimation except the best fit to experimental data, such a formal approach

nevertheless is used in a series of publications because of more or less degree of certainty in the presentation of MS. The main limitations of this approach are its formality and clear ignorance of effects of microstructure of PF on its CIP [16].

Modeling of MS based on account of microstructure

The microstructure (MST) of PF, which there is considered as the one manifesting itself by the grain size distribution law and the value of average grain size D_a of PF, is dependent on specific details of their processing ceramic technology [19]. This indicates that there are a rich variety of different ferrites supplied from various manufacturers which technologies used nevertheless differ and so MST, and since the modeling of MS for whole class of PF with the account of their MST is rather challenging task. In order to solve the problem in [21] it has been suggested that whole body of PF samples is possible to separate into two groups: the one for samples with a rather perfect, defectless MST (named as intrinsic quality group, IQG, assumed as reference one) and the another one for all the others (typical technical quality group, TQG). This division allows for PF of IQG to relate the magnetization process directly with material MST and to apply quantitatively the concept that experimentally observed characteristics of the sample in fact are integral ones appearing as such in the process of natural averaging their inner parameters over the ranges set up by the grain size distribution.

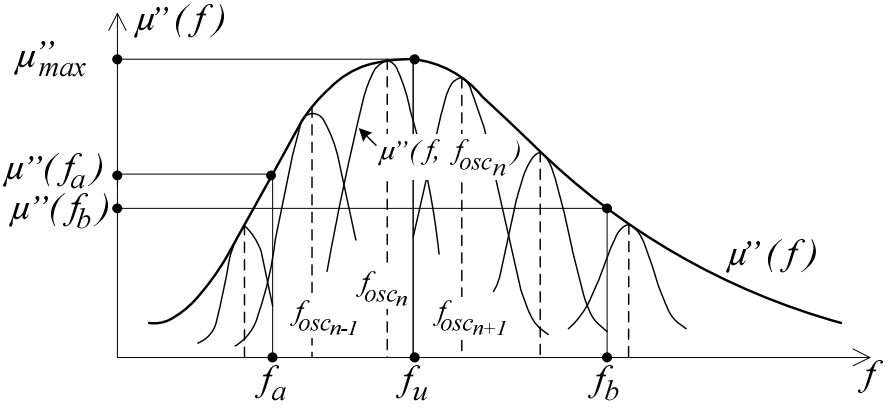

Fig.3. **Parameters of ACp ($\mu''_{\max}$, f_u , $\mu''(f_a)$, f_a , $\mu''(f_b)$, f_b) as well as the demonstration of concept for ACp composition by absorptions of elementary oscillators**

This concept translated to MS allows assuming for ferrites from IQG that every polycrystal grain of the sample can be considered as the low loss oscillator (the grain with DW having $\mu_{stat} \propto D$ and resonating at $f_{osc} \propto 1/D^2$ with D standing for the current gain size). As a consequence, e.g., the whole curve of ACp $\mu''(f)$ can be formed up from absorption curves of these tiny oscillators (having the absorption line $\mu''_{osc}(f)$ of Eq.7 form) with continuously distributed f_{osc} (for clarity in Fig.3 the principle is shown as if ACp $\mu''(f)$ would be compassed up only by the group of several oscillators). Accepting further (in accord with the experiments [20]) that the grain size distribution probability density function is log-normal:

$$\varphi(D) = (\log e / \sigma_D D\sqrt{2\pi}) \exp[-(\log D - \log D_m)^2 / 2\sigma_D]^2$$

where σ_D and $\log D_m$ are the distribution parameters of $\log D$, and relating the parameters of current absorption line of oscillator with current value of grain size, after integration over full range of the oscillator resonant frequencies, it is possible to obtain the mathematical form of ACp [21]:

$$\mu''(f) = \mu''_{\max} \exp[-(\log f - \log f_u)^2 / 2\sigma^2] \ , \qquad (8)$$

where $\mu''_{\max}$ and f_u, Fig.3, are characterizing the absorption maximum of $\mu''(f)$; $\sigma = 2\sigma_D$.
The potentialities of Eq.8 in presentation of MS (for different values of σ) as normalized curves are shown in Fig.4, *a*: it can be seen that the change of σ (which in the reality means the change of grain distribution) allows to go from deeply relaxation type of spectra ($\sigma = 0.6$) to clearly resonant one ($\sigma = 0.2$), having the distinguishing boundary value near *0.5* (in the process the dispersion components DCp were calculated by the use of KK relations, Eq.5).
For definite experimental spectrum $\mu''_{\exp}(f)$, under the assumption that it and that of Eq.8 coincide, the specific value of σ for the presentation of given MS is possible to evaluate from a complimentary point on the curve $\mu''_{\exp}(f)$ at frequency f_a:

$$\sigma = (1/\sqrt{2\ln \mu''_{\max}/\mu''(f_a)}\,)\left|\log f_u/f_a\right| , \qquad (9)$$

(particularly for $\mu''(f_a) = 0.5\mu''_{\max}$ and corresponding frequency denoted as $f_a = f_{0.5}$, i.e. for half-level absorption $\sigma = 0.85\log(f_u/f_{0.5})$).

Applications of the modeling to experimental MS

In the case of practical use of Eq.8 for definite MS it should be recalled that the modeling was developed for samples from IQG and frequencies corresponding to large amplitude dispersion region. As such the results of modeling has been applied to MS of high quality YIG (Fig.5, data from [22]) showing a close agreement with this symmetrical MS ($\sigma = 0.7$). The value of standard deviation obtained just for grain size distribution $\sigma_D = \sigma/2 = 0.35$ in this case correlates well with the typical values $(\sigma_{\ln D} \approx 0.5)/\ln 10 \approx 0.22$ for normal grain growth structure of PF [23]. Thus the results gained show that principles of modeling are realistic.

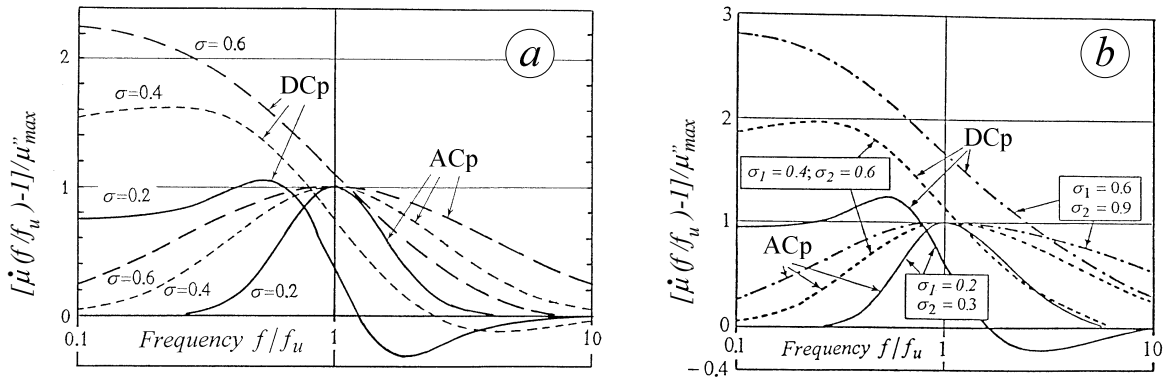

Fig.4. **Normalized theoretical MS: *a* – with the symmetrical (for IQG samples) and *b* – with the asymmetrical absorptions (for TQG samples)**

Even so, the majority of experimental MS show asymmetrical absorption curves $\mu''(f)$. In [17] it was shown that for presentation of these MS it is possible to use Eq.8 as well but by applying two values of σ: one, σ_1 for $f < f_u$ and another, σ_2 for $f > f_u$. Corresponding frequency dependences by thus modified Eq.8 in normalized form for several combinations of σ_1 and σ_2 (naturally $\sigma_2 > \sigma_1$) are shown in Fig.4, *b* – they really are depicting the most typical features of experimental MS. The physical background for this modification comes from the fact that majority of real samples (of industry technology) belongs to TQG of PF. This implies that in coarser grains having higher dimensions there are intragrain defects pinning DW and thus fragmenting their displacement. This rises the shift in the frequency response in relation to that of IQG because instead of one, low frequency $f_{osc}^{(LF)}$ (corresponding to oscillating DW of full size within larger size grains) there appear several

higher frequencies $f_{osc}^{(HF)}$ corresponding to vibrations of the fragments of pinned DW; this is lowering the value of σ_1 and increasing that of σ_2; the values thus gained only indirectly are

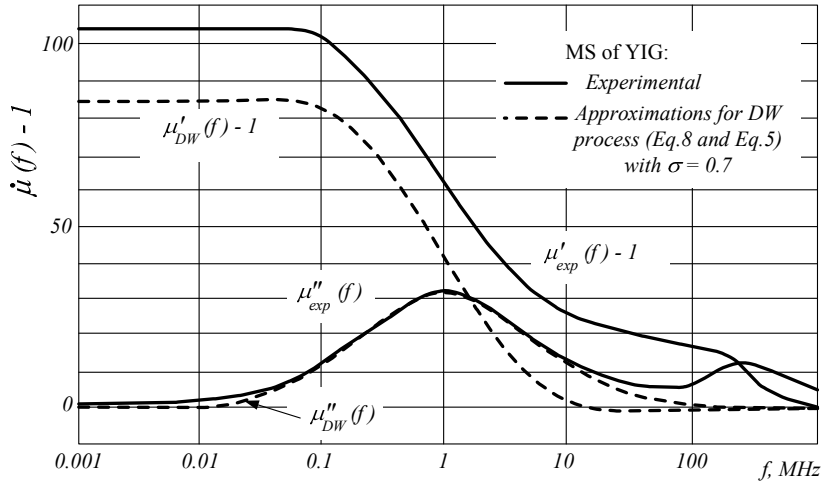

Fig.5. **Wide frequency range experimental MS of YIG and its approximations for large-amplitude dispersion range DW process**

related to actual grain size distribution. For approximation of the definite MS specific values of σ_1 and σ_2 is evaluated similarly as for σ but by the use of Eq.9 with two frequencies: f_a for σ_1 and f_b for σ_2 (Fig.3). Approximation of experimental $\mu''(f)$ in Fig.2 ($x = 0.39$) based on modified Eq.8 ($\sigma_1 = 0.63$; $\sigma_2 = 0.80$) show a close agreement between both thus demonstrating usefulness of such modification.

Conclusions

In relation to anomalous loss of PF it is shown that considerable contribution to it may come from DW processes which manifest themselves at radiofrequencies as the large amplitude dispersion of CIP. At present more rigorous analytic modeling based on realities – account of microstructure effects of PF is possible for absorption component of CIP for samples from high, intrinsic quality group (as a rule of laboratory production). In this case the modeling reveals that type of CIP spectrum – resonance or relaxation is determined by actual grain size distribution function which directly governs the distribution of resonance frequencies of oscillators – vibrating DW.

For samples from the group of usual technical quality (the majority of industrial technology magnetics) adequate analytic presentation of absorption component is possible as well but it is less strictly related to the grain size distribution since the coarser grains within sample are with intragrain defects effectively pinning DW. This creates misshape of symmetrical absorption – there appears more pronounced absorption at higher frequency. Reflection of this reality needs one additional parameter in the presentation.

In both cases the frequency dependence of dispersion component of CIP is obtained by the use of effective computer program for Kramers-Kronig relations.

This modeling, based on the concept that magnetic characteristics of the sample directly relates from that of log-normally distributed grains, as a whole is clearly productive since it allows not only to model the spectra of CIP (i.e. low field object) but permits to anticipate what happens with those spectra in increasing fields – both alternating and polarizing ones. In the first case the increase of amplitude is unpinning DW in coarser grains of the sample and

thus is increasing the value of low frequency permeability and lowering its f_u. In the second case it is necessary to notice that coercitivity of grains $H_C \propto 1/D$; it means that increasing polarizing field first of all is saturating these coarser grains thus lowering low frequency permeability and increasing f_u. Both statements are in line with the experiments.

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