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# Law of approach to magnetic saturation in nanocrystalline and amorphous ferromagnets with improved transition behavior between power-law regimes

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A B S T R A C T

New law of the approach to magnetic saturation is proposed based on scaling in ferromagnets with random magnetic anisotropy. This law is consistent with the known laws derived within perturbation theory in extreme cases, but it describes the transition mode between the power-low asymptotic regimes better. The improved law is proper for reliable fitting the approach magnetization to saturation in nanocrystalline and amorphous ferromagnets.

## 1. Introduction

Initially, the use of the law of approach to magnetic saturation (LAMS) was experimental determining of saturation magnetization by extrapolation of empirical LAMS expressions to the infinite field [1]. Since the publication of Akulov's paper [2], LAMS became the method for determining the local magnetic anisotropy energy (magnetic anisotropy energy of crystallites) in polycrystalline ferromagnetics. For the structural defect size being comparable or smaller than the width of the domain wall, the consideration of exchange interaction between the structurally uniform volumes is important. The first LAMS taking into account exchange interaction was derived by Brown [3]. Due to the competition between magnetic disorder and magnetic order caused by the exchange interaction, the LAMS is closely associated with the magnetic correlation length which depends on the applied magnetic field $R_H = (2A/M_s H)^{1/2}$, where $A$ is an exchange stiffness constant, $M_s$ is the saturation magnetization and $H$ is the applied field. The state of nonuniform magnetization with magnetic correlations with specific length $R_H$ is known as magnetization ripple [4–6]. The magnetic correlations were taken into account by Néel, Kronmüller, Schlömann and Malozemoff [7–12] to derive the certain LAMS (usually presented by specific power law $M \sim H^{-n}$) referred to the specific structural defect. It was noticed by Ignatchenko and Iskhakov that unique relationship between specific LAMS expression with a specific structural defect cannot be considered as reliable, because one certain LAMS may correspond to a variety of structural defects [13,14]. Using the random field theory Ignatchenko, Iskhakov [13,14] and Chudnovsky [15,16] have shown that the specific form of LAMS refers exceptionally to the correlation function or the spectral density of random magnetic anisotropy. It was found that the LAMS in all the types of media with random magnetic anisotropy with monotonically decreasing correlations are characterized by the following general behavior. Above a specific exchange correlation field $H_R = 2A/M_s R_c^2$, $M(H)$ follows to Akulov's LAMS ($M \sim H^{-2}$), and below it the power-law $M \sim H^{-n}$ with an exponent $n < 2$ depending on the spatial dimension of the random anisotropy inhomogeneity holds [13–15,17]. Thus, it was shown that monitoring this change in power mode of the LAMS can be used to determine the exchange field $H_R$. The $H_R$ values supplemented by independent measurements of $A$ and $M_s$ were used to study the structural correlation lengths in some amorphous alloys [14,18–23].

## 2. Micromagnetics

Let us describe the background and the basic results on micromagnetics briefly concerning LAMS. Nonuniform orientation of local easy magnetization axis (random magnetic anisotropy) of any nature (crystallographic, magnetoelastic etc.) results in the specific state with nonuniform magnetization – stochastic magnetic structure in nanocrystalline magnet. The LAMS in ferromagnets with stochastic magnetic structure is directly determined by the variance ($d_m$) of reduced transverse magnetization component ($\vec{m}(\vec{x}) = \vec{M}(\vec{x})/M_s$):

$$M(H) = M_s(1 - d_m(H)), \quad (1)$$

The key characteristic of stochastic magnetic structure is the

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correlation function of magnetization $C_m(\vec{r})$ or the spectral density $S_m(\vec{k})$:

$$\langle \vec{m}_\perp(\vec{x})\,\vec{m}_\perp(\vec{x}+\vec{r})\rangle = C_m(\vec{r});$$
$$\langle \vec{m}_\perp(\vec{k})\,\vec{m}_\perp(\vec{k}')\rangle = S_m(\vec{k})\delta(\vec{k}-\vec{k}');$$
$$C_m(\vec{r}) = \int S_m(\vec{k})\, e^{i\vec{k}\vec{r}}\, d\vec{k}. \quad (2)$$

According to [13,14,16] the variance of magnetization $d_m \equiv C_m(r=0)$ or more precisely its major term in perturbation theory is determined by spectral density $S(\vec{k})$ or by correlation function $C(\vec{r})$ of local easy magnetization axis:

$$d_m = \frac{R_H}{8\pi}\left(\frac{A}{K}\right)^2 \int C(\vec{r})\, e^{\frac{-r'}{R_H}} d\vec{r}' = \left(\frac{A}{K}\right)^2 \int \frac{S(\vec{k})\,d\vec{k}}{(k_H^2+k^2)^2} \quad (3)$$

where $K$ is a constant of local magnetic anisotropy, $k_H = 1/R_H = (MH/2A)^{1/2}$ is a wave vector of exchange magnetic correlations and $R_H$ is their correlation length. If we use exponential decay for correlation function $C(\vec{r})$ of local easy magnetization axis $e^{-r/R_c}$, the result for isotropic 3-d media is:

$$d_m = \frac{(aH_a)^2}{H^{1/2}\left(H_R^{1/2}+H^{1/2}\right)^3}. \quad (4)$$

Here $H_a = 2K/M_s$ is a local magnetic anisotropy field, $a$ is a coefficient equal to $1/15^{1/2}$ for uniaxial anisotropy, $H_R = 2A/M_s R_c^2$ is an exchange field, $R_c$ is a correlation length of local easy magnetization axis. There is transition between two power-law regimes – above and below $H_R$:

$$d_m = (aH_a)^2 \begin{cases} H^{-2} & , \quad H \gg H_R \\ H^{-1/2}H_R^{-3/2} & , \quad H \ll H_R \end{cases}. \quad (5)$$

In the log-log plot $d_m$ versus $H$ it is observed as two different angles of two linear parts – above and below $H_R$ (see Fig. 1). If we choose another monotonically decreased function $C(\vec{r})$ in Eq. (3), then we get new expression for $d_m(H)$, but the asymptotic power laws remain to be the same.

## 3. The problem

Investigators have no exact $C(r)$ from the experiment. Therefore, it is a problem to select the LAMS that should be used for the fitting of experimental approach to saturation data, but we can try to compare the quality of fittings by different LAMS expressions (for example derived by using $C(r) = \exp(-r/R_c)$ and $C(r) = \exp(-(r/R_c)^2)$ [22,24,25]). In this respect, after corresponding data processing the authors in [22,24,25] have determined a better correlation function $C(r)$. We will show that LAMS being derived using (4) does not fit experimental transition behavior between extreme power laws of approach to saturation. In the experimental data processing using LAMS analysis of plot lg $d_m$ versus lg $H$ can be used instead of fitting. However, in a typically practical case, when available experimental data are in the intermediate range between the asymptotic power modes, the procedure cannot be carried out.

In the paper we propose a new LAMS that describes the experimental approach to saturation magnetization curves in the intermediate region between the asymptotic power modes much better than the previous LAMS expressions. This feature makes the law suitable for reliable fitting the approach to magnetic saturation data.

The Eq. (4) is an example of possible analytic LAMS expression, that can be used for fitting the experimental data. However, it implies certain difficulties. To clarify the problems let's present the data on the approach to saturation in the following form. The replacement of the asymptotic power modes $M(H)\sim H^{-1/2}$ to $M(H)\sim H^{-2}$ with increasing $H$, predicted by Eq. (4) can be represented as a replacement of the exponent in empirical terms $M(H)\sim H^{-\alpha}$ that describes a small curve section near some certain field $H$. This technique has been used previously for the analysis of the theoretical LAMS expressions in thin magnetic films [26]. The details of the corresponding data processing are illustrated in Fig. 1 for the curve $\Delta M(H)/M_s \equiv (M_s - M(H))/M_s$ measured in nanocrystalline alloy FeSiBNbCu [18,27]. The exponent α is determined as the tangent slope in Fig. 1 at a small curve section near the current field $H$ from $H-\Delta H/2$ to $H+\Delta H/2$. A quite short width $\Delta H$ is selected in order to consider the corresponding curve section as linear in log-log plot, but it is made long enough for minimizing the experimental error in the tangent slope. The values α determined by the technique above are shown in Fig. 2, along with theoretical curves $\alpha(H)$ calculated as $\alpha = \frac{\Delta \ln(d_m(H))}{\Delta \ln(H))}$. The theoretical functions $d_m(H)$ are calculated using integrals (3) for $C(r) = e^{-r/R_c}$, $C(r) = e^{-\left(\frac{r}{R_c}\right)^2}$ and $C(r) = \theta(R_c - r)$, where $\theta(x)$ is Heaviside step function. The replacement of the asymptotic power modes (Fig. 2) from $M(H) \sim H^{-1/2}$ to $M(H)\sim H^{-2}$ is significantly more abrupt in the experiment than it is presented by theoretical curves (1)-(3). Although, the change of power modes by curves (1)–(3) is more abrupt for the case of a more abrupt decrease of $(r)$, it demands changing the applied field by at least three orders of magnitude. The experimental transition from α=0.5 to α=2 holds with changing the applied field by one order. Such a sharp change in power modes is observed experimentally in various amorphous and nanocrystalline alloys with LAMS analysis as in Fig. 1 [18,28–35].

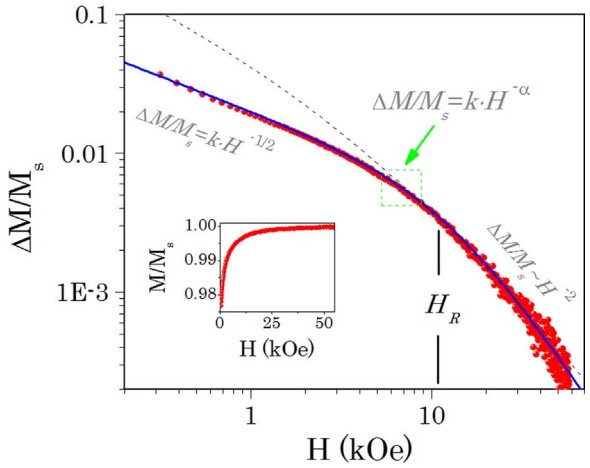


**Fig. 1.** The field of the crossover in the approach to magnetic saturation of the nanocrystalline alloy FeSiBNbCu. The arrow and the rectangle illustrate the determination of $\alpha(H)$. The Eq. (9) is the black solid curve and Eq. (5) is dashed.

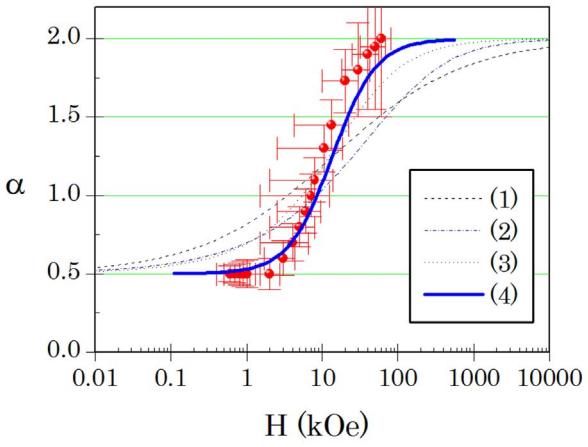


**Fig. 2.** Experimental values of exponent α in nanocrystalline alloy FeSiBNbCu (points) and theoretical curves calculated as $\alpha = \frac{\Delta \ln(d_m(H))}{\Delta \ln(H))}$. The $d_m(H)$ for the curves (1–3) are calculated using integrals Eq. (3) and $C(r) = e^{-r/R_c}$, $C(r) = e^{-\left(\frac{r}{R_c}\right)^2}$ and $C(r) = \theta(R_c - r)$ correspondingly. The curve (4) is calculates using Eq. (9).

## 4. Discussion

The discrepancy between experimental data and the theoretical curves calculated using Eq. (3) will lead to unreliability of fitting parameters by corresponding LAMS. To solve the problem, we consider the physical phenomena underlying the transfer between the asymptotic power modes in LAMS using the idea of scaling.

Let's rewrite the Eq. (4) using variable substitution as follows:

$$d_m(H) = a^2\left(\frac{R_c}{\delta}\right)^4 \frac{R_H/R_c}{(1+R_c/R_H)^3}. \quad (6)$$

The characteristic scale of nanostructure ($R_c$) and the scale which is determined by $\delta=\sqrt{A/K}$ magnetic constant as well as the length $R_H$ depending on the magnetic field are presented in Eq. (6). For this case the asymptotic power modes in Eq. (6) that is equivalent to Eq. (5) are the following:

$$d_m = a^2\begin{cases} R_H^4/\delta^4 & , \quad R_H \ll R_c \\ R_c^3 R_H/\delta^4 & , \quad R_H \gg R_c \end{cases}. \quad (7)$$

If $R_H = R_c$ (i.e. $H \gg H_R$), then the magnetic fluctuations are uncorrelated, else if $R_H \gg R_c$ (i.e. $H \ll H_R$), then there is a strong magnetic correlations and another LAMS power-law is present.

Further, we perform several estimations. The magnetic anisotropy constant averaged within the magnetic correlation volume (with the size of $R_m$) is estimated as $\langle K\rangle_m = K/\sqrt{N} = K(R_c/R_m)^{d/2}$. In this case, the LAMS can be represented as a result of competition of random magnetic anisotropy energy $\langle K\rangle_m$ localized on $R_m$ scale and the energy of the applied magnetic field $M_sH$. This representation is similar to the principal assumptions used for the derivation of Akulov's LAMS. In this respect, we can use Akulov's LAMS replacing the local anisotropy constant of crystallite $K$ by the magnetic anisotropy constant averaged within the magnetic correlation volume $\langle K\rangle_m$:

$$\frac{\Delta M}{M_s} = \left(\frac{2a\langle K\rangle_m}{M_sH}\right)^2 = \left(\frac{2aK}{M_sH}\right)^2 \cdot \left(\frac{R_c}{R_m}\right)^d. \quad (8)$$

The transition from $R_m = R_H$ ($H \ll H_R$) to $R_m = R_c$ ($H \gg H_R$) can be described as $R_m = R_H + R_c$ [36–38]. If we put the expression $R_m = R_H + R_c$ to the Eq. (8) we get the LAMS which is totally coincided with the LAMS of Eq. (4) derived based on the perturbation theory. Let's assume, that it is not size $R_c$, but the volume of the crystallite $R_c^d$, which is the smallest scale of the magnetic correlations. Afterwards we can describe this transition as $R_m^d = R_H^d + R_c^d$, and then using Eq. (8), we obtain a new LAMS expression:

$$d_m(H) = \frac{a^2}{\delta^4} \times \frac{R_H^4}{1 + (R_H/R_c)^d} = \frac{(aH_a)^2}{H^{\frac{4-d}{2}}\left(H^{d/2} + H_R^{d/2}\right)}. \quad (9)$$

The asymptotic power law in this LAMS are the same as in Eq. (4) and Eq. (5). It was found out that the replacement of the asymptotic power modes in Eq. (9) is more abrupt than the one obtained from Eq. (3) and the values of α calculated for this LAMS are closer to the experimentally observed data (see Fig. 2). The quality of fitting by using the LAMS of Eq. (9) is appropriate (Fig. 1). The fitting parameters $H_R$ =(11 ± 1) kOe and $H_a$ =(3.3 ± 0.4) kOe obtained with the help of Eq. (9) are in good agreement with the data obtained from the log-log analysis of LAMS [18,27]. The Eq. (9) has been successfully used in fitting the magnetization curves in [39–41].

## 5. Conclusion

The laws of approach to magnetic saturation in a ferromagnetic material with random magnetic anisotropy derived by using the perturbation theory are characterized by changing power-law modes with variation of the applied field at least by three orders of magnitude. In the experiment there is a sharper change in power modes within one order magnitude change in the applied field. We propose a new law of approach to magnetic saturation using idea of scaling for a ferromagnetic material with random magnetic anisotropy. It matches the expressions derived in the perturbation theory in extreme cases, but it describes the transition mode between the power laws better. We found that this law is suitable for reliable fitting the approach to magnetic saturation in nanocrystalline and amorphous ferromagnetics.

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