



**HAL**  
open science

# THE PREDICTION OF POWER LOSSES IN SOFT MAGNETIC MATERIALS

G. Bertotti, F. Fiorillo, G. Soardo

► **To cite this version:**

G. Bertotti, F. Fiorillo, G. Soardo. THE PREDICTION OF POWER LOSSES IN SOFT  
MAGNETIC MATERIALS. Journal de Physique Colloques, 1988, 49 (C8), pp.C8-1915-C8-1919.  
10.1051/jphyscol:19888867 . jpa-00229131

**HAL Id: jpa-00229131**

**<https://hal.science/jpa-00229131>**

Submitted on 4 Feb 2008

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## THE PREDICTION OF POWER LOSSES IN SOFT MAGNETIC MATERIALS

G. Bertotti, F. Fiorillo and G. P. Soardo<sup>1</sup>

*Istituto Elettrotecnico Nazionale Galileo Ferraris, GNSM-CNR and CISM-MPI, I-10125 Torino, Italy*

**Abstract.** – Deterministic methods studying the losses due to the motion of single Bloch walls or of well defined domain structures yield equations of limited accuracy, which only provide some hints as to the trend of power losses in different materials. These results are compared with the ones obtained through a recently developed statistical treatment of the loss processes, which predicts with good precision hysteresis and dynamic losses *vs.* frequency and induction, on the basis of a very limited input information.

### 1. Introduction

The prediction of power losses in magnetic materials is an old problem, which has never been given a rigorous solution. A successful approach would actually require the development of a powerful constitutive equation of magnetization, capable of accounting for the very complex phenomenology of hysteresis. This equation should involve a large number of intrinsic and structural parameters controlling the magnetization process. But we are still far from all of this, and we must resort to approximate, phenomenological models. These, on the whole, provide a good insight into the physical problems, and further suggest some practical guidelines, much required for actual applications.

In this paper the present knowledge on the prediction of power losses will be summarized. Attention will be focussed on materials for electrical use, i.e. grain-oriented (G.O.), non-oriented (N.O.) SiFe and amorphous laminations. Deterministic *vs.* statistical models of losses will be considered, stressing merits and drawbacks. Emphasis will be placed on some recent steps forward towards a better understanding of losses, obtained through a global statistical approach. Many aspects of the origin of losses, however, are still obscure, and some hints will be given as to the possible future directions of research.

### 2. The hysteresis loss

A much used procedure in loss investigations is the so-called separation of losses, in which total losses  $P$  are divided into static and dynamic components  $P_h$  and  $P_d$ . The hysteresis loss  $P_h / f$  is the limit of  $P/f$  for  $f$  (magnetizing frequency) tending to zero, while  $P_d$  is assumed to be the sum of classical and excess losses  $P_{cl}$  and  $P_e$ , so that

$$P = P_h + P_d = P_h + P_{cl} + P_e. \quad (1)$$

$P_{cl}$  is the loss of an ideal material uniformly magnetized, that is free of any domain structure. Equation (1) is not just a simplifying assumption, but has important physical meaning [1, 2].  $P_h$  originates from dissipative processes extremely localized in space and time (say  $< 10^{-7}$  s and  $10^{-7}$  m [3]). Clearly  $P_h / f$  is expected to be independent of magnetizing frequency and, a fortiori, of exciting field waveform, lamination thickness and resistivity. The accurate prediction of  $P_h / f$  would require a sound theory of ferromagnetic hysteresis, which, as previously mentioned, has not yet been proposed.

To a first approximation, the coercive field  $H_c$  can be taken as a good measure of  $P_h$ , but even so things are far from being simple. In all studies of coercivity one realizes that Bloch wall motion or nucleation is affected in real materials by energy fluctuations. In crystalline materials, inclusions, dislocations, internal stresses, grain boundaries, surface imperfections provide such fluctuations, but topological effects due to domain structure also play a role. In amorphous ribbons local inhomogeneities, giving rise to anisotropy and stress fluctuations, and surface imperfections appear as the main sources of  $H_c$  [4].

To predict  $H_c$  we must then first characterize the material microstructure through suitable parameters, which is often a difficult task. In G.O. laminations, with many  $180^\circ$  walls,  $H_c$  due to bulk impurities can be calculated from well known formulas [5-7], once concentration, dimension, morphology of the inclusions are determined. Internal stresses can be disregarded in well annealed strips, but other, less quantifiable, contributions may complicate the problem. For one thing, transverse flux closure domains, whose fractional volume  $V_Q$  increases with increasing misorientation of the [001] axis *vs.* rolling direction, hinder the motion of  $180^\circ$  walls: a proportionality relation between  $H_c$  and  $V_Q$  has indeed been found [8]. Surface pinning [9] and domain nucleation [10] may also play a leading role on coercivity, while more complications arise when longi-

<sup>1</sup>Permanent address: Dipartimento di Anatomia e Fisiologia dell'Università, I-10125 Torino, Italy.

tudinal compressive stresses accidentally set up. To reduce magnetoelastic energy, magnetization  $I_s$  may switch from the [001] to the [010] or [100] directions, thus producing a novel unfavorable transverse domain structure [11]. The resulting increases of  $H_c$  due to domain rearrangements are generally arduous to calculate. One can thus conclude that even in the seemingly simple case of well oriented SiFe laminations, the accurate predictions of  $H_c$  can be difficult if not impossible.

The situation is not at all easier in N.O. polycrystalline laminations. The currently available good quality products have a low impurity content. Thus the standard approach to calculate  $H_c$ , exclusively based on models of Bloch walls crossing a random assembly of inclusions, should be implemented considering the role of grain boundaries and crystallographic textures. However, very few studies in this direction were made and even the openly instructive case of polycrystalline pure iron still awaits deep investigations [12-14]. Experiments show that the overall dependence of  $H_c$  on impurities, average grain size ( $s$ ) and texture has the form

$$H_c = H_0 + A/\sqrt{\langle s \rangle}, \quad (2)$$

where  $H_0$  is a term related to impurities and  $A$  a parameter incorporating the effect of texture, at least in iron base alloys and for ( $s$ ) less than the lamination thickness [13, 14]. However, a quantitative theoretical explanation of the combined role of impurities, grain boundaries and texture has yet to be proposed.

But once the physical processes leading to coercivity are identified and  $H_c$  is evaluated, one still has to calculate losses, providing some basic clues on the properties of ferromagnetic hysteresis. In particular one wants to know the dependence of  $P_h$  on peak induction  $B_m$ : to this end, the use of the Preisach representation seems rather attractive [15-18]. As known, in this representation the macroscopic hysteresis loop is seen as the superposition of a large number of elementary rectangular loops, with reversal fields  $H^+$  and  $H^-$ . These may be associated with regions of the sample cross section, in which the magnetization is reversed by a large Barkhausen jump. In fine grained polycrystalline samples these regions are reasonably identified with single grains. The switching fields  $H^+$  and  $H^-$  are characterized by a suitable distribution function  $p(H^+, H^-) = f(H^+)f(-H^-)$  [16]. If nothing is known about  $f(H)$ , by experience a reasonable choice is a Lorentzian function [19]

$$f(H) = \frac{K}{1 + (H/H_m - 1/2)^2}. \quad (3)$$

$H_m$  is a measure of the distribution width and  $K$  is a normalization constant, upon integration of

$p(H^+, H^-)$  over the half plane ( $H^+, H^-$ ) for  $H^+ > H^-$ . Once  $H_m$  has been determined, the area of a given hysteresis loop between  $\pm B_m$  can be computed as

$$P_h = 4 \langle B_s \rangle f \int \int [(H^+ - H^-) / 2] \times p(H^+, H^-) dH^+ dH^- \quad (4)$$

where  $\langle B_s \rangle$  represents the height of the elementary Preisach loops. In G.O. SiFe  $\langle B_s \rangle$  equals the saturation induction  $B_s$ , while in isotropic materials because of the random orientation of crystallites we have  $\langle B_s \rangle \simeq 0.85 B_s$ .

Absolute predictions of  $P_h$  vs.  $B_m$  based on the knowledge of material microstructural properties can then be attempted, for instance by equating  $H_m$  with the estimated value of  $H_c$ . Conversely, if one single experimental value  $P_h^*$  at a given peak induction  $B_m^*$  is measured and fitted through equation (4),  $H_m$  and, consequently, the whole  $P_h$  vs.  $B_m$  behavior can be calculated. Typical results of such calculations are shown in figure 1, where experimental values of  $P_h$  in G.O. and N.O. SiFe laminations are compared with the theoretical predictions of equation (4). It must be stressed that the observed very good agreement over a wide range of  $B_m$  relies on the knowledge of a single free parameter  $H_m$ .

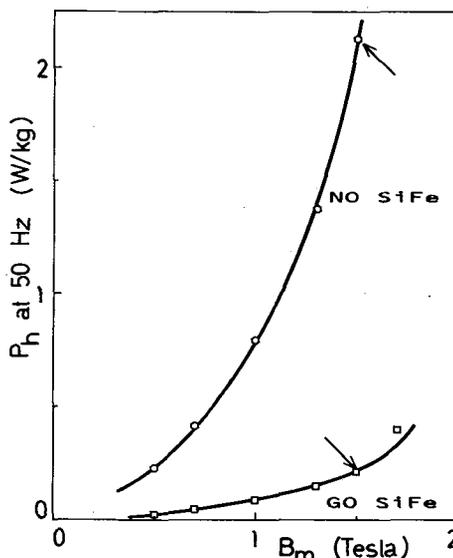


Fig. 1. - Comparison of experimental hysteresis loss component at 50 Hz vs. induction  $B_m$  on G.O. (squares) and N.O. (dots) SiFe, with theoretical predictions (full lines) based on the use of equation (4). For each material the parameter  $H_m$  (see text) is determined from a single experimental  $P_h$  value shown by the arrows.

### 3. The dynamic loss

It was previously stated that there is sufficient physical evidence supporting equation (1), with  $P_h/f$  (hysteresis loss per cycle) independent of  $f$ , although some particular processes may suggest marginal deviations from this constancy [20, 21]. It seems then appropriate, when studying the frequency dependence of power losses, to consider only those processes involving eddy currents circulation over a sufficiently large scale in time and space, beyond which Barkhausen discontinuities are smoothed out. The dynamic loss  $P_d$  is generally quite larger than the classical loss  $P_{cl}$ , the difference representing the so called excess or anomalous loss  $P_e$ . Williams, Shockley and Kittel [22] and later Pry and Bean [23] have accounted, quantitatively, for this difference, considering, respectively, the loss due to the motion of a single wall and of a system of equally spaced  $180^\circ$  Bloch walls. Pry and Bean model has been a very popular and much used one, since their ideal domain structure is close to the typical patterns of G.O. SiFe. The model provides a simple rule (just decrease the ratio  $2L/d$  between domain wall spacing  $2L$  and lamination thickness  $d$  to reduce  $P_d$ ), largely followed in actual applications. But one must also stress that only the gross features of the loss phenomenology can be explained by this model. Discrepancies between model predictions and experimental findings concern not only, all too often, the absolute values of estimated and measured dynamic losses, but especially the non-linear behavior of  $P_d/f$  vs.  $f$  (even in a perfectly oriented single crystal with a fixed number of walls [24, 25]), and the persistency of excess losses in very fine grained materials with  $2L/d \ll 1$ . Refinements to the Pry and Bean model can be made, if domain wall multiplication [10] and bowing [24] (two effects observed at increasing  $f$ s) are properly taken into account. Bishop, in particular, has considered the role of wall profile deformation (ruckling and bowing) on the non-linearity of  $P_d/f$  vs.  $f$  [26]. However, discrepancies are still observed between improved model and experiment, not only in polycrystals but also in perfect single crystals. On the other hand, it seems vain to push further the complexity of a purely deterministic approach, trying to take into account all the intricacies of the actual physical process.

One of the Authors (G. Bertotti) has reconsidered the whole matter, from a statistical point of view. To this purpose he has introduced a new physical entity, the "magnetic object" MO, which provides the local coherent magnetization reversal. An MO can be identified, in essence, with a group of strongly correlated domain walls, which, in the limit of loosely spaced domains, may coincide with a single wall or even a part of it. As a first consequence of this statistical approach, the classical loss turns out to be some background contribution, related to the superposition of eddy currents

due to different MO's. The loss separation implied by equation (1) is then further justified and we can now discuss the excess loss term  $P_e$ . The basic physical assumptions on the properties of the MO's can be summarized as follows [25]:

a) in a given cross-section  $S$  of the lamination  $\tilde{N}_0$  MO's are available for a certain macroscopic flux reversal, each MO being characterized by a reversal field  $H_r$ ;

b) the reversal fields span over a range, which depends on a distribution function; this, to a first approximation can be taken to be flat, with constant density  $1/(\tilde{N}_0 V_0)$  (as a second approximation a Lorentzian distribution, such as equation (3), can be used);

c) in each MO the magnetic flux reversal occurs at a rate  $\dot{\Phi}$  determined by the local eddy current damping. A damping excess field  $H_e$  can be defined as

$$H_e = \sigma G \dot{\Phi}, \quad (5)$$

where  $\sigma$  is the material conductivity and  $G$  is a mobility coefficient, whose value is known. This excess field can also be written as

$$H_e = P_e / \dot{B} \quad (6)$$

where  $\dot{B}$  is the induction rate of change;

d) due to the actual distribution of reversal fields  $H_r$ , only a fraction  $\tilde{n}$  of the total number of MO's in a given cross section will simultaneously reverse the magnetization at a given frequency, to produce the macroscopic flux rate  $S\dot{B} = \tilde{n}\dot{\Phi}$ . From equation (5) we obtain:

$$\tilde{n} = \sigma G S \dot{B} / H_e. \quad (7)$$

When  $f$  (i.e.  $\dot{B}$ ) is increased, the same tends to occur to  $H_e$  (Eq. (7)), which requires a higher driving field to obtain the magnetization reversal, but this at the same time excites new MO's, recruiting them to the magnetization process. The very fact that  $\tilde{n}$  increases with  $\dot{B}$  will then account for the fact that  $H_e$ , or actually the excess loss per cycle  $P_e/f$ , does not increase according to a linear law with  $f$ , but less rapidly, in a non-linear way.

According to equations (6, 7),  $\tilde{n}$  is a quantity which can be easily determined from measurements of losses (see also Eq. (1)), of  $\dot{B}$  and of some parameters of the given sample. Actual losses per cycle  $P/f$  vs.  $f$  relative to G.O. SiFe and FeBSiC amorphous ribbons are reported in figure 2a. From these experimental data, using equations (6, 7), we can calculate  $H_e$  and  $\tilde{n}$ , and in figure 2b we report  $\tilde{n}$  vs.  $H_e$ . These can be considered as alternative representations of the  $P/f$  vs.  $f$  curves, which transform into straight lines obeying the equation

$$\tilde{n} = \tilde{n}_0 + H_e / V_0 \quad (8)$$

where  $\tilde{n}_0$  is the number of MO's simultaneous active for  $f \rightarrow 0$ , which, as seen, is of the order of 1, at least for the considered materials. The slopes of the

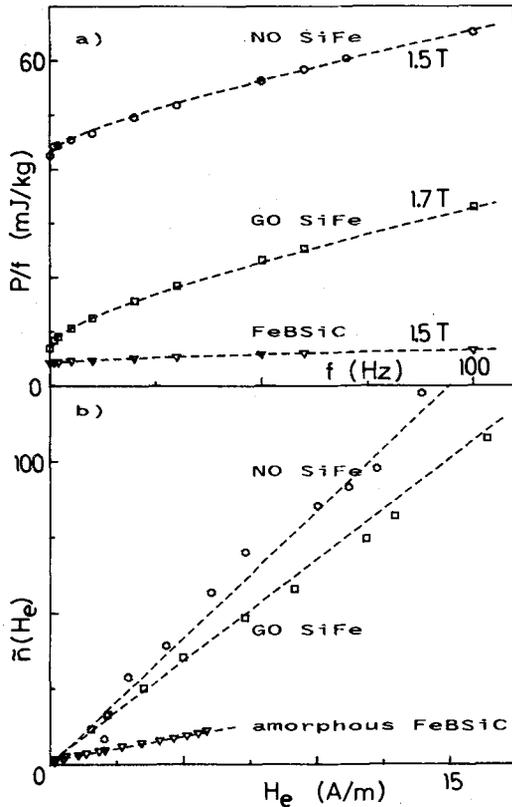


Fig. 2. - a) Experimental power loss per cycle  $P/f$  vs. frequency  $f$  measured on G.O. (squares), N.O. (dots) SiFe and amorphous FeBSiC (triangles); b) Curves of figure 2a transform into straight lines obeying equation (8), when plotting number of magnetic objects  $\bar{n}$  vs. excess field  $H_e$  calculated from experimental data using equations (6, 7). One finds: for G.O. SiFe sample:  $\bar{n}_0 = 1$  and  $V_0 = 0.15$  A/m; for N.O. SiFe sample:  $\bar{n}_0 \simeq 0$  and  $V_0 = 0.12$  A/m; for FeBSiC ribbon:  $\bar{n}_0 = 1.3$  and  $V_0 = 0.63$  A/m. Using these values and a theoretical loss expression similar to equation (10) (without disregarding  $\bar{n}_0$ ) the dashed curves of figure 2a can be computed [27].

lines of figure 2b are related, according to equation (8), to the width of the distribution function  $V_0$  and are thus closely dependent on the characteristics of given materials [27].

If we introduce equation (8) into equation (7) and  $\bar{n}_0$  is neglected, we find for the excess loss  $P_e$

$$P_e = 8\sqrt{\sigma G S V_0} B_m^{3/2} f^{3/2}. \quad (9)$$

In equation (9)  $V_0$  is the only unknown parameter, representative of the global microstructural properties of the material.

We can then summarize in a single expression the equation derived from the proposed statistical considerations, which should permit one to calculate total

losses of a given material for any peak induction  $B_m$  and magnetizing frequency  $f$ . We can write:

$$P = P_h + P_{cl} + P_e = f P_0(B_m) + \pi^2 \sigma d^2 B_m^2 f^2 / 6 + 8\sqrt{\sigma G S V_0} B_m^{3/2} f^{3/2}. \quad (10)$$

In this equation  $P_0$  represents the hysteresis loss per cycle, which, as previously discussed, can be calculated once the parameter  $H_m$  has been determined using a single hysteresis loss measurement  $P_h^*$ , or estimated from microstructural considerations. The well known expression of the classical loss appearing in the last member of equation (10) is easily calculated at any  $B_m$  and  $f$ , just knowing the lamination thickness  $d$  and its conductivity. Finally the last term, representing the excess loss, can also be easily calculated after determining  $V_0$ , again from a single experimental evaluation of an excess loss  $P_e^*$ . We can conclude that from the measurements of two loss values only (an hysteresis one  $P_h^*$ , and a total loss  $P^*$ , from which  $P_e^*$  is obtained) at arbitrary values of  $B_m$  and  $f$ , making

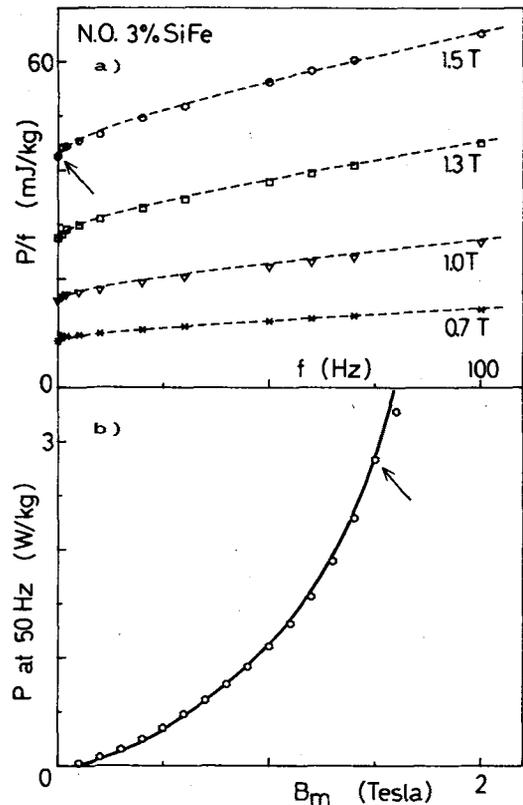


Fig. 3. - Comparison of experimental (dots) and theoretical (lines) losses for N.O. SiFe. Equation (10) is used for theoretical loss prediction: both parameters  $H_m$  and  $V_0$  were estimated from a single hysteresis loss value marked by arrow. a) power loss per cycle vs. frequency at different inductions; b) total losses at 50 Hz vs. induction.

use of equation (10) we can calculate the complete dependence of losses on peak induction and magnetizing frequency. Furthermore, one finds that in fine grained laminations the parameter  $V_0$  can also be expressed in terms of the hysteresis loss value  $P_h^*$  [28]. For these materials one single hysteresis measurement permits to determine both  $H_m$  and  $V_0$  and to calculate total losses over the whole ranges of  $B_m$  and  $f$ .

In figure 3a we compare  $P/f$  vs.  $f$  curves measured and computed according to the discussed procedure at different values of  $B_m$  for a typical N.O. SiFe sample, while in figure 3b the comparison concerns the experimental and computed  $P$  vs.  $B_m$  curves. All calculations rely on a single measurement of the hysteresis loss per cycle, actually evidenced by an arrow in figure 3a.

The very good agreement between experimental and calculated losses observed in figures 3a and 3b stresses the fact that for the first time we can predict correctly the dependence of hysteresis and dynamic losses per cycle for any frequency and induction.

#### 4. Conclusions

In discussing the general problem of loss prediction in magnetic laminations, it has been shown that the present state of knowledge, based both on deterministic and statistical approaches, provides a general framework which permits one to obtain practical information. Many aspects of the actual loss mechanisms are still poorly understood, and will certainly require intensive experimental and theoretical research efforts probably for many years to come. However, some important, significant progress has recently been made through a theoretical treatment based on a statistical approach, which provides rather careful predictions of losses for a variety of materials and in a vast range of magnetizing frequencies and work inductions.

- [1] Bertotti, G., *J. Appl. Phys.* **54** (1983) 5293.
- [2] Bertotti, G., *J. Appl. Phys.* **55** (1984) 4339 and 4348.
- [3] Allia, P. and Vinai, F., *J. Appl. Phys.* **48** (1977) 4649.
- [4] Kronmuller, H. and Groger, B., *J. Phys. France* **42** (1981) 1285.
- [5] Neel, L., *Ann. Univ. Grenoble* **22** (1946) 299.
- [6] Dijkstra, L. J. and Wert, C., *Phys. Rev.* **79** (1950) 975.
- [7] Hilzinger, H. R. and Kronmuller, H., *J. Magn. Magn. Mater.* **2** (1977) 11.
- [8] Kuppers, D., Kranz, J. and Hubert, A., *J. Appl. Phys.* **39** (1968) 608.
- [9] Celasco, M., Masoero, A., Mazzetti, P. and Stepanescu, A., *IEEE Trans. Magn.* **MAG-22** (1986) 502.
- [10] Bertotti, G., Fiorillo, F. and Sassi, M. P., *J. Magn. Magn. Mater.* **23** (1981) 136.
- [11] Swift, W. N. and Wolfe, G. F., *IEEE Trans. Magn.* **MAG-12** (1976) 244.
- [12] Degauque, J., Astie, B., Porteseil, J. L. and Vergne, R., *J. Magn. Magn. Mater.* **26** (1982) 261.
- [13] Ferro Milone, A. and Fiorillo, F., *Proc. Soft Magn. Mater. Conf. 7* (Blackpool) 1985, p. 75.
- [14] Barisoni, M. and Fiorillo, F., *this Conf.*
- [15] Della Torre, E. and Kadar, G., *IEEE Trans. Magn.* **MAG-23** (1987) 2820 and 2823.
- [16] Biorci, G. and Pescetti, D., *Nuovo Cimento* **7** (1958) 829.
- [17] Del Vecchio, R. H. and Charap, S. H., *IEEE Trans. Magn.* **MAG-20** (1984) 1437.
- [18] Bertotti, G., *Proc. 3rd Conf. Phys. Magn. Mater.* (Eds. W., Gorzkowski, H. K., Lachowitz and H., Szymczak) (World Scientific Publ. Co, Singapore) 1986, p. 489.
- [19] Bertotti, G., Fiorillo, F. and Soardo, G. P., *IEEE Trans. Magn.* **MAG-23** (1987) 3520.
- [20] Sasaki, T., Horie, N., Imamura, M. and Yamada, O., *J. Magn. Magn. Mater.* **19** (1980) 358.
- [21] Seagle, D. J. and Charap, S. H., *J. Appl. Phys.* **53** (1982) 8299.
- [22] Williams, H. J., Shockley, W. and Kittel, C., *Phys. Rev.* **80** (1950) 1090.
- [23] Pry, R. H. and Bean, C. P., *J. Appl. Phys.* **29** (1958) 532.
- [24] Narita, K. and Imamura, M., *Proc. Soft Magn. Mater. Conf. 3* (Bratislava) 1977, p. 403.
- [25] Bertotti, G., *J. Appl. Phys.* **57** (1985) 2110 and 2118.
- [26] Bishop, J. E. L., *IEEE Trans. Magn.* **MAG-20** (1984) 1527.
- [27] Bertotti, G., *IEEE Trans. Magn.* **MAG-24** (1988) 621.
- [28] Bertotti, G., *J. Phys. Colloq. France* **46** (1985) C6-389.