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RECENT PROGRESS IN SILICON IRON

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Résumé: Les progrès des recherches sur la recristallisation secondaire et sur la préparation des aciers pour l'électrotechnique sont brièvement illustrés. Le développement de méthodes pour la mesure des pertes locales et de modèles théoriques des pertes magnétiques dans ces matériaux sont discutés.

Abstract: A brief review is given on progress in preparation and understanding scondary recrystallization processes in electrical steels. The recent advances in measuring localized power losses and in theoretical modeling of losses in soft magnetic materials are also presented.

1) - INTRODUCTION

In this review paper we will first briefly refer on understanding secondary recrystallization processes in grain oriented silicon iron (GO SiFe), and on preparation methods (notably surface laser scribing), and on non oriented steels. The recent advances obtained in our laboratory in the measuring techniques, to detect and analyze local power losses, and in some new theoretical approaches to the problem of understanding the origin of power losses in magnetic laminations will then be examined. Apologies are due to the many authors who have contributed to this type of studies, whose work, however, cannot be given the due relevance here, because of space limitations.

2) - PROGRESS IN METALLURGICAL PROCESSES AND THEIR UNDERSTANDING

2-1) Grain oriented silicon iron laminations

A number of surveys have been published on studies and production methods of GO SiFe /1-3/. Therefore, only the most recent advances will be examined in this paper. Industrial techniques to produce GO SiFe are at present stabilized, since a great variety of primary grain growth inhibitors have been studied. A notable progress toward loss reduction has, however, been obtained with the laser scribed laminations /4,5/. The conventionally made GO steels still represent a large fraction of total market of oriented materials. Two tendencies should, however, be noted: from the production side, the move towards lower thicknesses, to obtain some loss reduction; and from the application side, the choice (mainly in the USA) of lower working inductions in transformer design. The capitalized lower core losses seem to compensate fo the larger dimensions and investement problems /6/. The optimum thickness is at present of the order of 0.23 mm for industrial frequencies applications /7/. Whenever working induction is reduced, higher permeability and lower loss materials, such as the high permeability GO SiFe developed some years ago, are no longer economically advantageous, because of the diminished difference, at lower inductions, of magnetic losses. This tendency, however, is not shared in Europe, where higher induction le-

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vels enhance the interest for higher permeability, lower thickness laminations, and probably for laser scribed ones /4,5,8/.

For what concerns recrystallization, progress has characterized in recent years the understanding of these phenomena. As known, the origin of such perfect (110)<001> texture in high permeability materials is not completely understood. Interesting work has recently been performed by carefully studying, by ODF techniques, the texture at different sheet depths in the successive production stages, starting from the hot band /9/. It was shown that the secondary grains nucleate immediately below the lamination surface, and the ultimate reason for the Goss texture formation is that during cold rolling shear deformation takes place at the surface, and the shear texture of bcc metals is (011)<100>. The surface nuclei grow because of their much larger size at the expense of orientations such as (111)<211> by selective rapid growth, due to the favorable angle between the two orientations.

A more general discussion outlining the role of a special 27° angle between (110)'s in SiFe for selective growth of (110)<100> oriented crystals is given in Ref. /10/. At about the same time Inokuki et al. /11/ studied the incipient stages of secondary recrystallization by transmission Kossel techniques, showing that the secondary Goss nuclei grow immediately below the surface, in form of flat grains at the expense of primary grains, which mainly have orientations (111)<112>, (111)<110>, (120)<001>, (100)<001>. Also Tanino et al. /12/ have obtained similar results for the site of nucleation of secondary grains, further showing the relevant effect of interpass aging during the different passes of cold rolling, to obtain a dislocation texture particularly favorable for a high perfection Goss texture. On high permeability materials with AlN as inhibitor, besides MnS, Matsuo et al. /13/ show that a combination of large grains and coarse precipitates favors a perfect texture. These secondary grains grow as colonies at the expense of primary fine grains, mainly having orientations (554)<225>. Partial phase transformation and critical cooling rate in boiling water after hot rolling are essential to produce local inhomogeneities in the structure, which favor the perfection of the texture. Lu et al. /14/ reexamine on the AlN inhibited materials the problem of the texture disuniformity at different lamination depths and of the optimum cold rolling, showing that when the cold reduction is less than 82% the deviations from ideal Goss texture becomes larger. Studies were also performed by computer models and experimental methods on the fact that during recrystallization, due to the action of inhibiting precipitates, a reduction of grain size dispersion occurs, bringing to a growth stagnation of the primary grains /15/.

Finally, the role of grain boundary surface energy /16/ and of primary structure on the improvement of Goss texture in high permeability materials was theoretically investigated, evidencing the parameters which control the selectivity of grain growth /17/.

2-2) Non oriented silicon iron laminations

Recently exhaustive review papers on non oriented electrical steels were presented by Brissonneau /18/ and Matsumura et al. /19/. Once again only very recent work on these materials will be covered in the present paper. The quality of materials was improved by further reductions of impurities, and apparently as of now the limits due to available raw materials seem to be attained by the present production techniques. A better quality of non oriented steels was recently developed by Shimayama et al. /20/ by vacuum melting and single stage cold rolling, by carefully controlling all possible factors giving rise to high losses, which were essentially related to the presence of occasional small quantities of Ti and Zr, forming carbides and some internal oxidation of Al present in the final annealing. For what concerns the top non oriented lamination qualities, in effect the addition of some Al to increase the resistivity, without substantial increase of brittleness, is frequently proposed /19/. However, with the addition of Al the problem of avoiding the alloy internal oxidation during final annealing becomes difficult. A careful research on this topic was recently done by Huneus et al. /21/ and by Geiger /22/.

Further improvements of losses and of working inductions have essentially been obtained in the last years in non oriented silicon iron by obtaining some favorable partially oriented texture, possibly close to (100)<hkl>. A steel of this type and of very high quality was recently developed by Goto et al. /23, 24/ by Sb additions, which give selective grain growth inhibition and by a two stage cold rolling with intermediate annealing. Some texture is also present in the steel developed by Shimoyama et al. /20/. Recently some research on the development of partial cubic texture was also developed by Verdun et al. /25/, and the effect on losses of partial texture formation with different cold rollings and annealings was studied by Page at British Steel Corporation. On alloys with lower silicon content some interesting work on the changes of texture after decarburizing heat treatments at different temperatures and temper annealing reductions were done by Rastogi et al. /26/. The fact that temper rolling eventually yields poorer textures seems of particular interest.

3) - PROGRESS IN MEASURING AND UNDERSTANDING POWER LOSSES

3-1) Introduction

Understanding the origin of power losses is clearly the first step to possibly improve the quality of GO SiFe laminations. However, any investigation of the loss problem strictly limited to the case of this material can probably distract the attention from a series of possible loss mechanisms, because of the tendency to oversimplify the problem: although it is generally recognized that dynamic losses in excess of the "classical ones" arise because of the presence of a domain structure, the attention, all too often, has been essentially focussed on a simple antiparallel domain one, typical of GO SiFe, with further drastic assumptions on the dynamic behavior of the corresponding Bloch walls. The most important recent advances in understanding the loss problem have been obtained when these oversimplifications have been dropped.

It is in fact well known, that losses in excess of the so called "classical ones" and the non-linear behavior of power losses per cycle vs. magnetizing frequency f, rather than representing an anomalous feauture of some materials (notably of GO SiFe) ar observed in all soft magnetic materials /27/. Therefore excess losses and non-linearity cannot be the product of a specific domain pattern,but must result from some mechanisms common, to various degrees, to all magnetic materials. On the other hand, these studies of loss anomalies, as stressed, have been essentially based on the analysis of the behavior of antiparallel domain structures, yielding the well known Pry and Bean (PB) model /28/. Excess losses are essentially proportional to the ratio 2L/d of bar domain spacing 2L to lamination thickness d. This result proved very important, since it provided a general guideline towards the reduction of losses in SiFe, pointing to the need of reducing 2L/d. Loss improvements along this road were actually obtained:

a) by developing special coatings capable of exerting relatively large tensions, which through magnetostrictive action would reduce supplementary structure /1/ and the antiparallel domain size;
b) by suggesting to metallurgists the search of methods capable of producing some tilt of the (100) grain axis off the lamination surface: domain size would then be reduced because of magnetostatic effects /29/;
c) by introducing the use of some form of surface scribing, which again because of magnetostatic and magnetostrictive effects would reduce domain size and losses /4, 5,8/.

With all of these successful achievements based on the PB predictions, such models are still incomplete, since they fail in many instances to account for the actual loss behavior. In particular according to these models:

1) the non linearity of losses with f should not be present, unless some new mechanism is invoked to account for domain multiplication or wall bowing, which on the other hand are not always present in actual GO SiFe laminations;
2) in materials with small domain spacings with respect to thickness, excess losses should be absent, in contrast with actual observations /27/;
3) even in materials with relatively large 2L/d, the quantitative agreement between theoretical and measured eddy current losses is quite often not satisfactory, and the decrease of domain size obtained by one or more of a)-c) methods determines dynamic loss reductions in general lower than expected from the PB model.

All of these failures are due to the extreme idealization of the model, partly because of the simplifications of the chosen domain geometry and mostly because the model assumes perfectly uniform and continuous motions of all domain walls. Any further pro-

gress towards a better understanding of power losses imposes two conditions:
A) the development of new methods to study in great detail very localized magnetization processes and their contribution to losses;
B) the development of theoretical models taking account of more complex domain configurations and also taking in due consideration the disuniformities and the discontinuities characterizing in general domain wall motions.

Both these subjects have been the object of intensive research in our laboratory, and the main results obtained so far will be summarized in the following sections.

3-2) Approximate loss theory provides clue for local power measurements

Rigorously, we can assert that the mechanism by which energy is dissipated in a conducting magnetic material is essentially the one of induced eddy currents. Let $\vec{J}(\vec{r},t)$ represent the eddy current density at a time t in a volume element dV located at $\vec{r}$ in the sample, and P be the average energy loss per unit volume. Then:

$$P = \lim_{T\to\infty} \int_{-T/2}^{+T/2} (dt/T) \int_V (dV/V) \; (|\vec{J}(\vec{r},t)|^2 / \sigma) \qquad (1)$$

where σ is the material conductivity. To make a rigorous use of Eq. 1, detailed knowledge of the magnetization rate in each sample volume would be needed. An approximate loss expression can be obtained if losses are calculated as a sum of contributions from eddy currents generated in ideal circuits shaped as hollow cylinders with square cross section of side 2x, thickness dx, oriented along the lamination axis /30/. One has:

$$P = a \; (\sigma / d^2) \int_{-\infty}^{+\infty} \varnothing \; (d/2, \omega) \; d\omega \qquad (2)$$

where a is a coefficient depending on 2L/d and on the ratio of peak to saturation inductions. $\varnothing$ (d/2, ω) is the power spectrum of the time derivative of the induction flux linked to a square area of side equal to the lamination thickness d of the sample cross section. The limits of this approximation have been examined /30,31/ in comparison with rigorous loss models, finding that errors involved in Eq. 2 are less than 10-15%. But the main interest of Eq. 2 is, from one side, that it permits to perform loss calculations (although approximate) also in the case of non uniform and discontinuous wall motions, provided the power spectrum $\varnothing$ is known, and, on the other side, that it relates local power losses in an elementary sample volume of cross section d^2 to $\varnothing(d/2, \omega)$, a quantity directly accessible to experimental measurements.

Two techniques were developed in our laboratory to measure $\varnothing$ and therefore to determine losses in such elementary sample regions, through Eq. 2. In the "point contact" one /32/, two pick-up probes are placed on the sample surface at a distance equal to thickness d. One then detects the emf induced by Bloch wall motions between the probes, the power spectrum of which is obtained by a spectrum analyzer. From Eq. 2, at each magnetizing frequency (which can be as low as 0.01 Hz) local losses are evaluated. Furthermore, from the spectrum shape, the statistical properties of domain wall motions can be studied: the cutoff frequency is in fact related to the average time taken by a wall to run beneath pick-up probes, and the slope of the spectrum provides information on the spread of these times over subsequent loops. From the emf time dependence one can also count the number of walls effectively taking part to the magnetization process. This method has already provided a variety of results /30,32/, permitting to study magnetization processes and losses in different sample regions, with various domain patterns, or under applied tension. Bishop /33/ has recently analyzed the information obtained from these local emf measurements and has suggested the use of arrays of four probes, to retrieve more detailed information on actual domain wall motions.

A second method, still based on the use of Eq. 2, was also developed in our laboratory, which makes use of an optical technique to study the dynamic local walls behavior and losses. The method is based on the Kerr effect: a polarized laser beam is employed and the reflected signal is frequency analyzed to obtain the power spectrum entering Eq. 2. The laser beam is focussed on regions of the sample surface of the order of the square of its thickness. Thanks to the properties of laser beams and to sophisticated experimental techniques, the optical method can be used also on very thin materials, such as amorphous ribbons /34/, more easily than the point contact one, although it cannot be used with coated SiFe laminations, since it requires a proper polishing of the sample surface.

3-3) The development of rigorous and general theories of power losses

The merit of the approximate loss approach is not only the one of taking account in some form of the stochastic character of domain structure and dynamics, but also, as stressed, of suggesting new methods to measure local power losses and domain behavior. Recently one of the authors (G. Bertotti) has further investigated the possibility of expressing power losses still starting from Eq. 1 but in a rigorous form. Maxwell equations were solved dropping the approximations which had led to Eq. 2, the only assumtions being that all elementary magnetization changes occur along the longitudinal axis of the sample and that transient responses are controlled by the reversible permeability μ . To take account of the random character of the magnetization changes with respect to position $\vec{r}$ and time t, space-time Forier transforms were used in the $\vec{k}$ and ω reciprocal spaces. The final, rigorous and general loss expression has the form /35/:

$$P = \sigma\,(4/S)\sum_{\vec{k}}\int_{-\infty}^{+\infty}(d\omega/2\pi)\frac{|\vec{k}|^2}{|\vec{k}|^4 + (\omega\sigma\mu)^2}\;S_{\dot{I}}\,(\vec{k},\omega)\;. \tag{3}$$

In Eq. 3, S is the sample cross section, the summation over $\vec{k}$ runs over a set of values determined by the boundary conditions, and $S_{\dot{I}}(\vec{k},\omega)$ is the statistical power spectrum of the rate of change of the magnetization $\dot{I}(\vec{r},t)$. On the other hand $\dot{I}(\vec{r},t)$ can be described by a random sequence of elementary magnetization changes taking place at different positions $\vec{r}_i$ and times t_i. From Eq. 3, losses can be separated in 3 terms: an hysteresis one P(hyst), due to the average energy spectrum of the single magnetization jump; a classical term P(class), resulting from the contribution to losses of the cross products of these jumps in the absence of correlation; and an excess or anomalous term P(exc) deriving from the same cross products (or equivalently from some eddy currents overlapping) in the presence of correlations. If these are described in terms of a Markov process, then the correlated cross part of the spectrum and losses can be expressed in terms of the transition amplitude $M(\Delta\vec{r}, \Delta t)$ giving the condition probability that two subsequent jumps take place at a relative distance $\Delta\vec{r}$ and with a time delay Δt.

Making use of Eq. 3 two special cases were studied in detail: the one of very fine grained materials with small domain spacings /36/, and the one of materials, such as GO SiFe, with large domain spacings /37/. In both cases the problem is to find the right physical form for $M(\Delta\vec{r}, \Delta t)$ to describe the actual geometrical and dynamical characteristics of the domain structure under investigation. Since in this paper we are mainly interested in GO SiFe, we will briefly refer to this case only. In the case of oriented materials with antiparallel domains and 2L/d>>1, the obvious assumption is that the single magnetization process is concentrated in few Bloch walls. With a proper choice of the $M(\Delta\vec{r}, \Delta t)$ function, a loss expression identical to the PB one can be obtained. However, in order to account for the non-linear behavior of losses with frequency, and to obtain calculated excess losses in closer agreement with experimental ones, the $M(\Delta\vec{r}, \Delta t)$ expression valid for the PB model is modified by a correction based on the assumption that, because of local coercive fields, the total surface of active walls is different from the one of all domains actually observed. The progressive increase of applied field reduces the irregularities of domain wall motions, and it is assumed that the field in excess of local coercive field H(exc) is proportional to wall velocity, which in turn is proportional to the increase of active wall areas. From these general assumptions, one finds that for large domain spacings, losses can be expressed by an equation of the form /36-38/:

$$P = P(\mathrm{hyst}) + P(\mathrm{class}) + B\,f\,\left(\sqrt{1 + A\,f} - 1\right) \tag{4}$$

where B and A are related to the actual surface of active walls and to the capability of applied field to increase this surface as f is increased. Eq. 4 can be considered as a generalization of the PB one, now capable of accounting for the effect of various loss mechanisms, such as motion irregularities, domain multiplication, wall bowing, and thus accounting for the non-linear behavior of losses vs. frequency. In particular for what concerns GO SiFe, it is found that experimental P/f vs. f curves are very well fitted by Eq. 4, by just choosing proper values for A and B. An expression identical to Eq. 4 is also found for the case of small domain spacings, where B and A are now related to some characteristics of the Barkhausen (B.) noise, whose statistical properties can be used to determine the structure of $M(\Delta\vec{r}, \Delta t)$.

Since very much the same equation is found both for very small and very large domain spacings, one may expect that a unique equation should in general express losses with parameters A and B strictly related to the geometrical and dynamical properties of the actual domain structure characterizing the investigated material. This point of view is confirmed by the fact that Eq. 4 is in both cases equivalent to the form /39, 40/

$$P = P(hyst) + P(class) + P(exc) = P(hyst) + P(class) + \sigma \dot{I} G \dot{\phi} \tag{5}$$

where $\dot{\phi}$ is the flux rate of change associated respectively with a single wall motion or with a B. type avalanche; G is a generalized damping coefficient, which is little dependent on the details of the domain structure and dynamics, as long as local flux changes contributing to losses are associated with space correlation ranges of the order or less than the sample thickness. In such cases G is closely equal to the value $G^{(w)}=0.1356..$ calculated by Williams et al. /41/ in their investigation on the loss contributions from the motions of Bloch walls in single crystals. The final step is then to make the assumption that an equation of the form (5) holds in all cases, independently of domain size, distribution and dynamic properties. Then the physical interpretation of this, now general, equation is the following one.

Dynamic loss behavior results from a competition between external magnetic field and various local internal fields, due to coercive, magnetostatic and eddy current effects. Strong internal fields tend to correlate different walls (especially in small grain materials) or sections of one same wall (typically in GO SiFe). The effect of these internal correlation fields is to concentrate active walls in groups called "magnetic objects" (MO) /39,40/. Any MO is characterized by a generalized damping coefficient G relating the magnetic pressure H(exc) acting on it to the velocity of local flux variation $\dot{\phi}$. But the relation between H(exc) and P(exc) is simply given by

$$H(exc) = \sigma G \dot{\phi} = P(exc)/\dot{I} \; . \tag{6}$$

For any value of f the magnetization process can be described in terms of a number $\bar{n}$ of active MO's randomly placed throughout the sample cross section. Taking into account that $\bar{n}$ must satisfy the condition

$$\bar{n} \dot{\phi} = S \dot{I} = 4 S I_{max} f \quad , \tag{7}$$

we also find

$$P(exc)/\dot{I} = H(exc) = H^{(w)}/\bar{n} \quad (8), \quad \text{where} \quad H^{(w)} = 4 \sigma G^{(w)} S I_{max} f \; . \tag{9}$$

Actually $H^{(w)}$ represents the dynamic field which would act if the whole flux variation were produced by the motion of a single MO. Therefore, $\bar{n}$ includes all relations between dynamic losses and the evolution of domain structure. For what concerns the properties of $\bar{n}$, we may notice that the motion of a single MO is opposed by the local coercive field and by the eddy currents counterfield corresponding to the excess field H(exc), which, on the other hand, tends to act as a further magnetic pressure on other MO's. This H(exc) tends to increase with f and provokes the activation of further MO's, thus determining the progressive homogeneization of the magnetization process. $\bar{n}$ should then in general be an increasing function of H(exc), and to the first order

$$\bar{n} = \bar{n}_o + H(exc)/V_o + \ldots\ldots \tag{10}$$

$\bar{n}_o$ being the number of active MO's in the limit of f=0. Thus V_o is equivalent to a characteristic field determining the capability of the applied field to increase $\bar{n}$ at increasing frequencies. By substituting Eqs. 6-10 into Eq. 5, one finds a general loss expression having a form similar to the one of Eq. 4, that is

$$P = P(hyst) + P(class) + (2\, I_{max}\bar{n}_o V_o)\, f \left(\sqrt{1 + \left(\frac{16\sigma G^{(w)} S\, I_{max}}{\bar{n}_o^2\, V_o}\right) f} - 1 \right) \qquad (11)$$

where $\bar{n}_o$ and V_o control the loss behavior respectively in the limit of low and high f. Comparing Eqs. 4 and 11 we can see how the A and B constants are related to $\bar{n}_o$, V_o, and to the other quantities characterizing the magnetization process.

In conclusion, Eq. 11 is found to express in general magnetic losses, provided the domain dynamics can be described in terms of a random distribution of MO's, and that the competition between applied field and various internal counterfields can be expressed by a simple linear relation such as Eq. 10. The loss of any material can be classified in terms of the parameters $\bar{n}_o$ and V_o, connecting losses to the structural and dynamic properties of magnetic domains. V_o has the dimensions of a field, which essentially controls dynamic losses and which should then be related to the material intrinsic characteristics. This relation has yet to be found on rigorous bases, but it is important to check whether actual losses obey Eq. 11, with appropriate selections of $\bar{n}_o$ and V_o. It is then preferable to plot the loss data, rather than in the conventional P/f vs. f plane, in another plane, with coordinates $\bar{n}$ and H(exc). According to Eq. 10, these plots should be linear, the slope representing $1/V_o$. From Eqs. 7-9, $\bar{n}$ and H(exc) can be evaluated at each frequency f. It can be noted that in this representation, magnetic systems obeying exactly the PB law should correspond to an horizontal line ($\bar{n}$ remains constant independently of the applied field), while classical systems should be represented by vertical lines ($\bar{n}$ tends easily to infinity determining the complete homogeneization of the magnetization processes).

In Fig. 1b some typical results are reported: the experimental points are obtained from actual loss measurements on various GO SiFe samples and on an amorphous material one, making use of Eqs. 7-9. As can be seen,these points closely lay on straight lines, thus obeying Eq. 10, which has essentially been postulated. Actually the behavior of $\bar{n}$ and H(exc) calculated for a variety of other materials, from their respective P/f vs. f curves, by means of the outlined procedure are also found to obey rather strictly Eq. 10, with drastic slope (i.e. $1/V_o$) variations for different materials. In particular, the case of an amorphous ribbon is also shown in Fig. 1b: it may be expected that domain structures of GO SiFe and of amorphous materials (wound up sample in toroidal form) may be strongly different from each other, which means that the MO's in the two cases hold little resemblance. However, as we can see, the proposed model accounts for loss behavior with great accuracy both in GO SiFe and in the amorphous material case.

Furthermore, making use of the $\bar{n}_o$ and V_o values determined from the plots of Fig. 1b and using Eq. 11, one can calculate P/f vs. f curves: examples are given for GO SiFe samples and for the amorphous sample in Fig. 1a, where points represent experimental measurements, and dotted lines are calculated by means of Eq. 11, using the $\bar{n}_o$, V_o data resulting from the plots of Fig. 1b. In all cases examined so far such very good fit between calculated and measured P/f vs. f curves has always been obtained /39,40/.

Investigations are now in progress, particularly for GO SiFe, in order to measure the special field V_o on materials of different perfection and permeability, on single crystals, under various stress conditions, in the presence or absence of coatings and of surface scribing. When a sufficient amount of data will be analyzed in the $\bar{n}$-H(exc) plane, it is hoped that some correlation may be found between V_o and the structural characteristics of the material, thus possibly providing suggestions for further loss reductions. But investigations on a variety of materials, besides the GO SiFe one, should certainly help to clarify the actual link which should exist between the field V_o (so important in controlling excess losses) and the intrinsic characteristics of the investigated material.

At present this link is not known, but some simple phenomenological considerations seem to indicate a close relationship between V_o (controlling dynamic losses) and (of all parameters !) the hysteresis loss /42/. In fact, if we consider the quasi static regime, the minimum field to obtain at least one active MO is certainly related to the hysteresis field, whose role becomes similar to the V_o one in the limit of

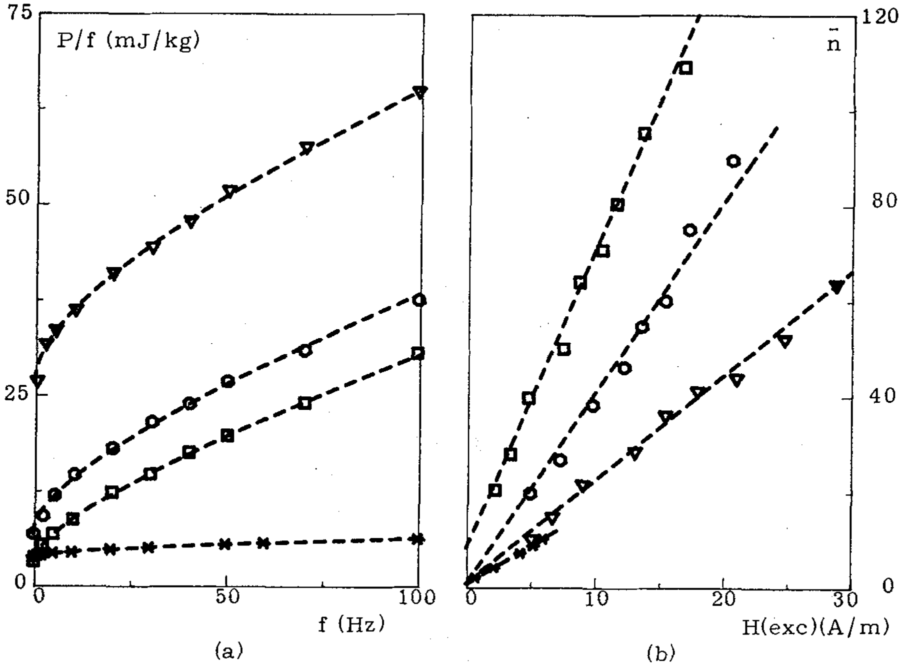

Fig. 1 - Power losses per cycle P/f vs. frequency f (left part (a)), as usually done in conventional plots, and in (b) number of active magnetic objects MO $\bar{n}$ vs. excess field H(exc) as calculated from experimental P/f vs. f loss data, using Eqs. 7-9. As seen, the calculated $\bar{n}$ - H(exc) points very closely obey linear laws, that is Eq. 10. Slopes of these lines permit to determine the characteristic field V_o, and their intercepts with the H(exc)=0 axis, the $\bar{n}=\bar{n}_o$ value for f=0. The dotted lines of Fig. 1a have been calculated from Eq. 11 and using the $\bar{n}_o$ and V_o values determined from Fig. 1b. Experimental points refer to different samples: squares, conventional GO SiFe lamination; open dots, same sample under a 50 MPa tensile stress; triangles, same sample after plastic deformation; crosses, toroidal wound up amorphous ribbon (Metglas 2605SC). For further details see Refs. /39,40/.

f=0. Following this line of reasoning, it has been found that a linear relationship should exist between V_o and the hysteresis loss /39,40,42/. The proportionality coefficient is directly related to the number of magnetic objects $\bar{N}_o$ (active or not) which are present in the material cross section. This relationship is very closely verified for a variety of magnetic materials, over at least two orders of magnitude of V_o /42/.

In conclusion this rigorous, and at the same time phenomenological, analysis of power losses, which takes proper account of the discontinuous and non uniform wall motions, is found to represent with great accuracy actual loss behaviors, not only in GO SiFe, but also in many other materials. Furthermore, the parameter V_o which essentially controls dynamic losses is found to be possibly related to the hysteresis field controlling the static ones. This seems to suggest the existence of some general principle, controlling the overall features of the magnetization processes, both in the static and in the dynamic conditions.

Further developments are then expected, which should help clarify in a unified model the problem of excess losses, not only in GO and non oriented SiFe, but also in many other magnetic materials.

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