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## ON THE EFFECT OF GRAIN SIZE ON MAGNETIC LOSSES OF 3% NON-ORIENTED SiFe

G. Bertotti, G. Di Schino<sup>+</sup>, A. Ferro Milone and F. Fiorillo*Istituto Elettrotecnico Nazionale Galileo Ferraris and G.N.S.M.-C.I.S.M.,  
I-10125 Torino, Italy*

Résumé - La variation des pertes en excès  $P_e$ , statique  $P_h$  et totales  $P_t$  avec la taille moyenne des grains  $g$  a été étudiée sur le FeSi 3% non orienté. Les résultats montrent que  $P_h$  varie en fonction de  $g$  selon la loi  $P_h = P_0 + A\sqrt{g}$ , où  $P_0$  et  $A$  sont respectivement liés à l'effet des impuretés précipitées et à la texture. On obtient aussi que  $P_e$  dépend de  $g$  selon l'expression  $P_e = B\sqrt{g}$ .

Abstract - The grain size dependence of total, static and excess losses has been investigated in 3% non-oriented SiFe laminations, produced by continuous casting. It is found that the static loss  $P_h$  varies with the average grain diameter  $g$  according to the law  $P_h = P_0 + A\sqrt{g}$ , where  $P_0$  and  $A$  are respectively related to the effect of precipitated impurities and to the texture. It is also obtained that the excess loss can be described by the expression  $P_e = B\sqrt{g}$ .

## I - INTRODUCTION

In the evaluation of 50 Hz core losses of ferromagnetic materials it is very convenient and conceptually appropriate to express the total loss  $P_t$  as the sum of a static, a classical and an excess contribution [1]:

$$P_t = P_h + P_c + P_e \quad (1).$$

The effect of material structure on  $P_t$  is incorporated in the behavior of the static loss  $P_h$  and of the excess loss  $P_e$ , the classical component  $P_c$  representing the limit to which  $P_t$  would reduce in the ideal case of a completely homogeneous magnetization process. In high grade SiFe non-oriented sheets  $P_h$  usually represents the dominant contribution to the total loss, but continuing refinement of material processing, leading to lower precipitated impurities content, larger grain sizes and also texture improvements, necessarily involves an increasing role of the excess loss  $P_e$ . In this paper we have made a detailed investigation on the behavior of the loss components in several batches of calcium treated non-oriented steel sheets, placing particular emphasis on the role of grain size, which was made to vary, through suitable thermal treatments, between 15  $\mu\text{m}$  and 400  $\mu\text{m}$ . It is found that  $P_h$  and  $P_e$  follow a  $1/\sqrt{g}$  and a  $\sqrt{g}$  law respectively,  $g$  being the average grain diameter. It is also

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<sup>+</sup>TERNI S.p.A., Terni, Italy

shown that, by appropriately fitting the loss vs. grain size curves, information is obtained on the contribution of precipitates to the static loss and on the effect of texture. The excess loss, whose very presence cannot be predicted on the basis of current theories of losses in ferromagnetic materials, is discussed, making use of a novel theoretical approach, developed by one of the authors [2].

## II - EXPERIMENTAL AND DISCUSSION

0.35 mm thick non-oriented laminations, nominally containing 3% Si and 0.4% Al, were produced by continuous casting. Desulfuration was achieved through treatment of the melt with CaSi (final S content less than 60 ppm). All the cold reduced sheets were then given a final decarburation treatment, followed by a short annealing at a temperature ranging between 1000 °C and 1100 °C. From electron microscope observations, the number of precipitates resulted of the order of 100 - 300 mm<sup>-2</sup> (diameter < 0.5 μm). The average grain diameter ranged, according to the annealing treatment, between 60 μm and 110 μm. The total loss per cycle  $P_t/f_m$  vs. the magnetizing frequency  $f_m$  was measured in the range 1 Hz - 200 Hz, at a peak induction  $B_M=1.5$  T. By extrapolating the  $P_t/f_m$  curve to the limit  $f_m \rightarrow 0$  the value of the static loss component was determined, which was checked in a number of cases through the measurement of the DC hysteresis loop with the ballistic method. The so obtained static and 50 Hz excess losses appear to be fairly scattered, as shown in Figs. 1 and 2 (the ensemble of small voids). This is due to the fact that, given a certain average grain diameter, a slightly different texture and/or precipitated impurities content characterize the material. It is also observed that the excess loss accounts in general, in correspondence of a grain size of the order of 100 μm, for a 15% - 20% of the total loss. In order to have a larger spectrum of grain sizes, selected sheets were subjected to a series of isochronal 1 h annealings, up to a maximum temperature of 1250 °C (\*). To avoid internal oxidation and the ensuing detrimental effects on the material magnetic properties, a vacuum furnace was employed and annealing was performed under a continuous flow of dry H<sub>2</sub>, at a partial pressure of 1 Torr. At each step the hysteresis loop, the  $P_t$  vs.  $f_m$  curve and  $g$  were measured. The results are summarized, for four different samples, in Figs. 1-a, 2-a and 2-b, respectively representing the behavior of  $P_h$ ,  $P_e$  and  $P_t$  as a function of  $g$ . One can see that the static loss decreases and the excess loss increases upon increasing the grain size, leading to a shallow minimum of total loss about  $g=200$  μm. The general behavior of such data is in qualitative agreement with previous literature results, related however to a much more restricted range of  $g$  and to an induction value of 1 T [3]. As shown in Fig. 1, the  $P_h$  vs.  $g$  behavior is in good agreement with a law of the type  $P_h = P_0 + A\sqrt{g}$  (broken lines). In Fig. 1-b, showing  $P_h$  as a function of  $1/\sqrt{g}$ , the parameters  $P_0$  and  $A$  appear respectively as the y-axis intercept and the slope of the least square fitting straight lines. This result, while showing on the one hand that the  $1/g$ , law usually assumed in the literature must be taken with caution, suggests, on the other hand, a natural physical interpretation for  $P_0$  and  $A$ . The additional contribution to the loss  $P_0$  is actually expected to arise mainly from the interaction of the Bloch walls with the precipitates. It ranges from 0.9 W/Kg to 0.6 W/Kg, approximately scaling according to the number of counted impurities.  $P_0$  can also be expressed in terms of an equivalent coercive field  $H_0 = P_0 \delta / 4B_M f_m$ , the half width of a rectangular hysteresis loop of area  $P_0 \delta / f_m$ , being  $\delta$  the material density. One finds  $15 \leq H_0 \leq 23$  A/m, to be compared with the equivalent total coercive field  $H_h = P_h \delta / 4B_M f_m$ , which is found to lie in the range  $34 \leq H_h \leq 48$  A/m, when  $g=150$  μm. As to the slope  $A$ , it appears to be related to the material texture, the higher the slope the more unfavourable the texture, as it is also confirmed by the behavior of the measured DC remanence.

(\*) A lamination having an initial grain diameter of 15 μm, obtained by 3 h annealing at 750 °C after cold rolling, was also heat treated.

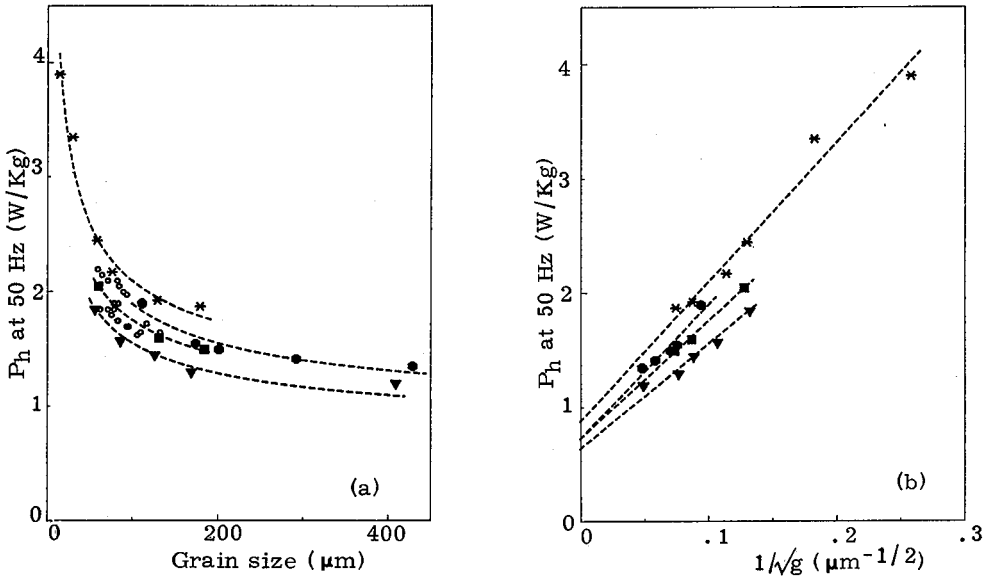


Fig. 1 - a) Static loss  $P_h$  vs. average grain diameter  $g$ . The scattered small voids correspond to the as-obtained sheets. Broken lines give best fitting, according to the expression  $P_h = P_0 + A/\sqrt{g}$ . b)  $P_h$  vs.  $1/\sqrt{g}$ . Note the different y-axis intercept  $P_0$  and slope  $A$  of the fitting straight lines.

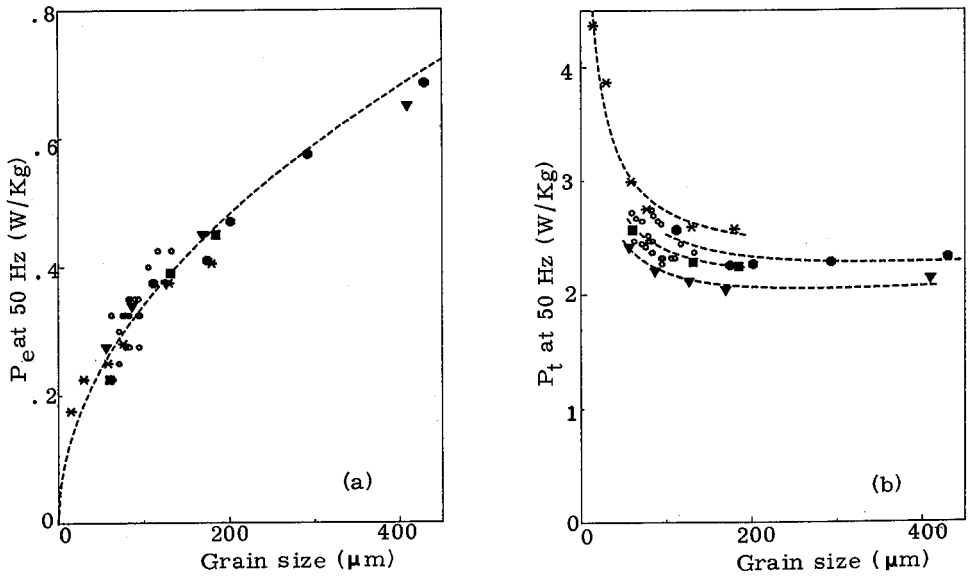


Fig. 2 - a) Excess loss  $P_e$  vs.  $g$ . The best fit line corresponds to the equation  $P_e = 3.4 \cdot 10^{-2} \sqrt{g}$  ( $g$  in microns). b) Total loss  $P_t$  vs.  $g$ . Broken lines are obtained from the best fittings of  $P_h$  and  $P_e$ , shown in Figs. 1-a and 2-a.

Concerning the grain size dependence of  $P_h$ , it must be remarked that early experiments [4, 5] and theoretical models [6, 7] point to a  $1/g$  behavior of the coercive field, which, however, does not fit into our results, obtained in a very wide range of  $g$ , that are consistent with a  $1/\sqrt{g}$  law. Such a law is substantiated by new experiments on extremely pure iron (A. Ferro Milone and F. Fiorillo, to be published) and also suggested by some recent work of Degauque et al. [8]. On the other hand, Goodenough predicts a coercivity proportional to the inverse of the average domain wall spacing [7], which is expected, on the basis of a simple calculation minimizing the sum of magnetostatic and wall energy in a grain, to vary as  $\sqrt{g}$ . Let us now examine the behavior of the excess loss  $P_e$ , by stressing first that current theories would not predict any detectable excess loss when, as in the present case, the ratio of domain wall spacing to the sample thickness is substantially less than 1. As previously remarked, we find instead a 15% - 20% contribution to  $P_t$  from  $P_e$  in an intermediate grain size region. Moreover, the sometimes invoked linear dependence of  $P_e$  on  $g$  does not agree with our data, which follow a definite  $\sqrt{g}$  law. From best fitting of the experimental points of Fig. 2-a we actually obtain  $P_e = 3.4 \cdot 10^{-2} \sqrt{g}$  ( $g$  expressed in microns). These results can be given a proper physical interpretation by making use of a novel loss theory, recently developed by one of the authors [2], in which the excess loss behavior appears to be regulated by the competition between the uniform action of the externally applied field and the spatial fluctuations of the local coercive fields, that are associated with the different Bloch walls in the material. Since the characteristic scale of such fluctuations substantially corresponds, in polycrystalline materials, to the grain dimension, a quantitative expression of the excess loss in terms of the hysteresis loss and average grain size can be obtained. As illustrated in a companion paper by G. Bertotti, the model correctly predicts the measured behavior of  $P_e$ , at least when  $g$  is smaller than the thickness of the sample. Having thus brought the problem of dynamic losses back to the features of the static hysteresis loop, it appears once more of fundamental importance to concentrate on the basic aspects of domain wall motion during static magnetization. This can be done with the help of Barkhausen noise experiments [9], which could provide the needed experimental link between the macroscopic properties of the hysteresis curve and the microscopic processes characterizing the reversal of magnetization.

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