Effect of Frequency on the Iron Losses of 0.5% and 1.5% Si Nonoriented Electrical Steels

Marcos F. de Campos¹, Taeko Yonamine¹, Marcos Fukuhará¹, Fernando J. G. Landgraf², Carlos A. Achete¹,³, and Frank P. Missell¹,⁴

¹Instituto Nacional de Metrologia, Normalização, e Qualidade Industrial—Inmetro, Duque de Caxias, RJ 25250-020, Brazil
²Departamento de Engenharia Metalúrgica e de Materiais, Escola Politécnica, Universidade de São Paulo, São Paulo, SP 05508–970, Brazil
³COPPE, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ 21941–972, Brazil
⁴Universidade de Caxias do Sul, Caxias do Sul, RS 95070-560, Brazil

The effect of grain size on iron losses were compared for two electrical steels with 0.5 and 1.5 wt% Si. The results confirm that the optimum grain size for minimizing the energy losses decreases when the electrical resistivity decreases or when the frequency increases. Experimental results are compared to a model which considers the influence of grain size. The recrystallization texture of the alloys varies little with grain size and consists mainly of the fibers {111}uvw and {110}//RD.

Index Terms—Electrical steels, grain size, loss modeling, texture.

I. INTRODUCTION

ELECTRICAL steels are widely used industrial materials, for example, as the core of motors or in transformers. Nonoriented steels are applied in rotating machines, and should have ideally random texture, of type {100}uvw, i.e., with the easy magnetization axis of body-centered cubic (bcc) iron parallel to the plane of the sheet, randomly distributed.

Aside from texture, another factor which influences losses in electrical steels is grain size. Several authors [1], [2] have pointed out the existence of an optimum grain size for minimization of losses. A model [3], based on both theoretical and experimental data, predicted that the optimum grain size for minimizing the energy losses decreases as: electrical resistivity decreases or frequency increases. The objective of this paper is to test the validity of that model in different circumstances, including in steels with different Si content (i.e., different resistivities) and with measurements performed over a larger frequency range and for different magnetic inductions. Although frequencies of 50–60 Hz are typical for most applications of electrical steels, operating frequencies of 400 Hz are encountered in aircraft [4]. Thus, another useful characteristic of the model [3] is providing insight into the loss behavior of steels at other frequencies.

II. EXPERIMENT

Two alloys were studied: 1) alloy A with 0.52 wt% Si, and resistivity = 20.5 μΩ·cm; and 2) alloy B with 1.53 wt% Si and resistivity = 32.2 μΩ·cm. Both alloys received different “skin-passes” (4–12% reduction in thickness), which resulted in different recrystallized grain sizes, after an annealing at 760 °C. Magnetic measurements were done in a Brockhaus model MPG 100D hysteresis measuring system (with Epstein frame), in the frequency range of 1–400 Hz, for a magnetic induction \( B = 1.5 \text{T} \). The magnetic measurements at quasistatic condition were made at a frequency of 5 mHz, also for a magnetic induction \( B = 1.5 \text{T} \). The texture was measured in a FEI Quanta 200 scanning electron microscope (SEM) equipped with a TSL system for electron backscattered diffraction (EBSD) analysis. The average grain size was measured parallel to the transverse section of the sheet, by the intercept method.

III. RESULTS AND DISCUSSION

The grain size was introduced as a variable using a simple metallurgical rule [5]: With increasing deformation (i.e., increasing thickness reduction), the energy stored during the deformation is greater, resulting in a larger number of recrystallization nuclei and a lower final recrystallized grain size. However, as the samples were submitted to different reductions, the thickness of samples is an additional variable; but, its effect can be separated in the model [3], by assuming that the anomalous loss component depends on the square of the thickness [6], [7].

A. Brief Description of the Model

According to the loss separation procedure, the total losses \( P_\text{t} \) are separated into three components

\[
P_\text{t} = P_\text{h} + P_\text{cd} + P_\text{an}
\]  

(1)

where \( P_\text{cd} \) is the classical eddy-current losses, \( P_\text{an} \) is the anomalous or excess losses, and \( P_\text{h} \) is the hysteresis losses, i.e., \( P_\text{h} \) is the area of the hysteresis curve in the quasistatic mode times the frequency \( f \)

\[
P_\text{h} = f \oint B dH
\]  

(2)

where \( B \) is magnetic induction and \( H \) is the applied magnetic field. If we suppose that the area of the hysteresis curve in the...
quasistatic mode is proportional to the inverse of the grain size \( G_s \) [3], [8], [9], then (2) becomes

\[
P_h = \left( a_1 + \frac{a_2}{G_s} \right) \cdot B_{\text{max}}^2 \cdot f
\]

where \( B_{\text{max}} \) is the maximum induction and \( q \) is the Steinmetz exponent, with typical value \( q = 1.6 \) [3]. \( a_1 \) and \( a_2 \) are constants to be experimentally determined. The classical eddy losses \( P_{cd} \) are given [10], [11] by

\[
P_{cd} = \frac{\pi^2 f^2 B_{\text{max}}^2 \ell^2}{6 \rho}
\]

where \( \ell \) is the thickness of the sheet and \( \rho \) is the resistivity. The deduction of the equation for the anomalous losses \( P_{an} \) has been previously described [3]. It was assumed that the anomalous loss component depends on the square of the thickness [6], [7]

\[
P_{an} = a_3 \cdot G_s^{3/2} \cdot \frac{1}{\rho} \cdot e^2 \cdot B_{\text{max}}^2 \cdot f^{3/2}
\]

where \( a_3 \) is a constant to be experimentally determined. The optimum grain size \( G_{\text{opt}} \) for minimizing the losses is

\[
G_{\text{opt}} = \left( \frac{a_4 \cdot \rho}{B_{\text{max}}^2 \cdot e^2 \cdot f^{1/2}} \right)^{2/3}
\]

where \( a_4 = (2a_2/a_3) \).

**B. Comparison of the Model With Experimental Data**

Fig. 1 shows that both alloys have an almost linear dependence of quasistatic loss \( P_{QS} \) with grain size, as expected from (6). \( P_{QS} \) (or \( Hc \)) \( \propto \gamma/M_s G_s \), where \( \gamma \) is the domain wall energy, \( M_s \) is the saturation magnetization and \( Hc \) is the coercive field. The slope for both steels is quite similar, because \( \gamma/M_s \) is very nearly the same for both compositions.

Figs. 2 and 3, where loss separation was applied according (1), show that the optimum grain size changes with frequency.
The texture of the samples is quite similar, with two fibers $\langle 111 \rangle//ND$ (ND = normal direction) and $\langle 110 \rangle//RD$ (RD = rolling direction) as the main texture components, almost not affected by grain size (see Fig. 6). However, the sample with the larger grain size [see Fig. 6(a)], has more Goss ($\langle 110 \rangle\langle 001 \rangle$) component and, presumably, better magnetic properties near the rolling direction. The texture is very similar to the other commercial nonoriented silicon steels [13], and is far from the ideal texture $\{100\}\langle 001 \rangle$.

IV. CONCLUSION

Experimental data indicates that the optimum grain size for minimizing the iron losses changes with frequency and resistivity. A model to predict the optimum grain size, taking into account variables such as sheet thickness, resistivity, frequency, and maximum induction has been described. The recrystallization texture of our samples presents two fibers $\langle 111 \rangle//ND$ and $\langle 110 \rangle//RD$ as main components.

ACKNOWLEDGMENT

This work was supported in part by the Brazilian agency Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). The authors M. F. de Campos, T. Yonamine, and M. Fukuhara would like to thank CNPq-PROMETRO for their support. The authors would like to thank L. Gomes for quantitative metallography measurements.

REFERENCES


Manuscript received March 10, 2006 (e-mail: fmissell@yahoo.com; fpmisell@ucsd.edu).