Anisotropy study of grain oriented steels with Magnetic Barkhausen Noise

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Abstract. Grain oriented electrical steels present strong anisotropy, due to a (110) <001> texture (Goss), with [100] direction parallel to rolling direction (RD) and [110] direction parallel to transverse direction (TD). MBN (Magnetic Barkhausen Noise) were employed to measure magnetic properties in several angles towards RD using a 15° step. For 90° to the rolling direction (i.e., TD), the MBN signal changes, decreasing the MBN rms. It is found a connection between initial permeability and MBN rms. The lower initial permeability for the TD is related to a larger contribution of irreversible rotation in the hysteresis. The MBN procedure is non-destructive and provides rapid understanding of the anisotropy of the material, without the use of laborious methods like Epstein frame or toroidal coils.

1. Introduction

Magnetic Barkhausen Noise (MBN) is a very important tool for non-destructive characterization [1-3]. Many studies [1-5] have focused on establishing a relation between the microstructure of steels and the MBN, which can be affected by crystallographic orientation [6]. Grain oriented (GO) steels present only the (110) [001] texture component, named as Goss. This is confirmed in SEM-EBSD analysis, showing that the microstructure of the GO steels consists in large grains, with ~0.5 mm of diameter, having only Goss orientation as texture component [7]. In the same GO sheet, different crystalline orientations can be evaluated, as the easy axis [100], [110], and the hard axis [111]. Thus, crystallographic orientation can be isolated as the only possible variable. Although the MBN was reported almost 90 years ago, its origin and characteristics remain not plentifully understood [8]. The MBN procedure is rapid and non-destructive and can provide understanding of the anisotropy of the material, without the use of laborious methods typically used for characterization of electrical steels like Epstein frame.

Experimental

Grain oriented steels sheets were kindly supplied by Acesita. The GO electrical steel has as physical characteristics: Silicon content 3.2%, thickness 0.27 mm and density d=7.65 g/cm³. Hystereses of the
GO electrical steels were measured in Epstein frame under quasi-static conditions. The measurements followed the requirements of IEC 60404-2 standard, including the sinusoidal shape of the magnetic induction. MBN measurements were carried out with portable equipment, named “Barktech”, developed at our laboratory in USP. Figure 1 shows a simplified sketch of this equipment. A sinusoidal wave current was applied to the MBN probe, with amplitude of 1 A and frequency of 10 Hz. The MBN signal was measured with a pick-up coil of high sensibility. The MBN sensor signal was amplified, band pass filtered, and sampled at a frequency of 400 kHz. The choice of 10 Hz as the alternating magnetic field frequency was due to the better signal to noise ratio. For this frequency (10 Hz), the effect of eddy currents is small (note also that the samples are thin and have high resistivity).

![Figure 1. Experimental setup for the MBN measurement.](image)

**Results and Discussion**

The anisotropy of magnetic properties is evident in the quasi-static hysteresis of Fig. 2. It is noteworthy the significant change of behavior about the permeability $\mu$ (Fig. 3). The permeability at 1.5 T ($\mu_{15}$) is minimum at $45^\circ$, while the initial permeability $\mu_i$ continuously decreases with increasing angle, with a point of minimum at $90^\circ$ (see Fig. 3).

A very simple analysis [9], focusing on the initial permeability $\mu_i$ (equation 1), provides insight about the competition between irreversible rotation and domain wall movement. Coercivity and initial permeability are closely related, and are inversely proportional, as seen at Fig. 3.

\[
\mu_i \cong \chi \left( \frac{\partial B}{\partial H} \right)_{H=0}
\]

(1)

Note: $\mu = \chi + 1$. $\chi$ is the magnetic susceptibility. $B$ is magnetic induction. $H$ is the applied magnetic field.

The Eq. 2 estimates the initial permeability supposing only occurrence of irreversible rotation, $\mu_{i(rotation)}$, without any domain wall (DW) displacement processes (in the deduction, it was supposed isotropic distribution of the magnetization of the domains) [9].

\[
\mu_{i(rotation)} \cong \chi_{i(rotation)} = \frac{B_i^2}{3\mu_0 K_1}
\]

(2)
Using the following values (~3%Si iron-silicon alloy): Induction of Saturation $B_s = 2.03$ T and First Order Magnetocryrstalline Anisotropy Constant $K_1 = 3.6 \times 10^4$ J/m$^2$ ($\mu_0$ is the permeability at the vacuum), it is obtained $\mu_{i(\text{rotation})} \cong 30$. However, the measured initial permeability is much above this value (Fig. 3). Thus, the contribution of irreversible rotation seems to be less relevant than DW movement. It should be noted, anyway, that irreversible rotation dissipates more energy than domain wall movement and this should contribute to increase the coercivity for the 90° sample.

![Hysteresis loops](image1)

**Figure 2.** Hysteresis loops for the grain-oriented electrical steel measured for the directions 0°, 45° e 90° to RD. Measurements performed at quasi-static condition (5-10 mHz), Epstein frame. This is a detail of the complete measurements. Fields upto 5000 A/m were applied, until the Induction of 1.5 T could be attained.

![Permeability and coercivity](image2)

**Figure 3.** Permeability $\mu_{15}$, initial permeability $\mu_i$ and coercivity $H_c$ as function of the angle to RD for the Grain-oriented steel (with Goss (110) [001] texture)

The data of Fig. 3 indicate that, for the sample 90°, part of the quasi-static losses is dissipated by means of domain irreversible rotation, at low inductions. This is probably due to 90° irreversible rotation of the magnetization of domains. The domain wall structure of GO steels is very peculiar, with 180° domain walls parallel to the rolling direction [10,11], see Fig. 4. If a field is applied in the 90° direction (i.e., TD), which is transverse to RD, domain wall movement is not possible (Fig. 4). In
In this case, 90° irreversible rotation has to occur before any domain wall movement, and this implies in lower initial permeability for the 90° sample.

Without observing the domain structure of GO steels (Fig. 4), it would be impossible to explain the behaviour found in Figs. 2 and 3. The hard axis [111] is at arc cos (1/√3) or 54.74° from RD. The lower permeability is expected for the 45° sample, which is near the 54.74° angle. In fact, permeability at 1.5 T (μ15) is lower for 45° sample, showing that dissipation by irreversible rotation is taking place in the higher inductions [12].

Figure 4. Domain structure of GO steels (schematic). The interface between the “stripes” represents 180° domain walls. The [100] axis is parallel to RD. Based on experimental pictures of refs. [10,11].

MBN signals are shown in Fig. 5. In the Figure 6, it is observed that the intensity of the MBNrms (root mean square voltage of MBN signal) is lower for the 90° direction sample, and this indicates that irreversible rotation is probably contributing more significantly for the reversal of magnetization for this direction. MBNrms is defined by the Eq. (3):

\[
MBN_{rms} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (V_i - V_{m})^2}
\]

(3)

Where Vi is the mean voltage, measured at a definite time; Vm the mean voltage of the entire signal and n the number of points of the MBN signal.

It can be seen from Fig.5 that the envelope of the MBN signal at 0° direction (RD) has larger amplitude than the envelopes from 45° and 90°. Barkhausen activity (avalanches) is more significant in this direction due to the large quantity of 180° Domains walls [6]. It is also observed that the MBN signals (Fig. 5) present a first and second maximum for RD, which was attributed by Hwang et al [13] to processes of DW nucleation and annihilation.

The MBN signal is mainly due to 180° domain wall moving [5,14]. Taking this into account, the MBN signals (frequency of 10 Hz) shown in Figure 5 should be compared with the initial permeability data (frequency of 5 mHz) shown in Figure 3. Steels with martensite (domain irreversible rotation is important reversal mechanism in this case, due to the nanocrystalline dimensions of the martensite) also present lower initial permeability, higher coercivity and lower RMS of MBN [15,16]. The same trend is observed here for the 90° direction of GO electrical steels, as it can be inferred from Figs. 3, 5 and 6.

Conclusions

When irreversible rotation of magnetization takes place, the MBN signal changes, decreasing the RMS of MBN (because the MBN is mainly due to domain wall motion, when irreversible rotation happens, the MBN activity is poor). It was found a connection between initial permeability and RMS of MBN. Lower initial permeability is related to a larger contribution of domain irreversible rotation in the magnetization reversal process. The MBN is a simple and rapid method to detect anisotropy in the steel sheets.
Figure 5. Magnetic Barkhausen Noise (MBN) signals for 0° (rolling direction), and for 45° and 90° from rolling direction. It can be noted that the signal is stronger for the rolling direction.
Figure 6 Polar plot of the RMS of MBN for the GO electrical steel. Angular step at 15°.

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References

[1] Lo C C H, Jakubovics J P, Scruby C B 1997 IEEE Trans. Magn. **Mag-33** 4035
[2] Kikuchi H, Ara K, Kamada Y, Kobayashi S 2009 IEEE Trans. Magn. **Mag-45** 2744
[3] Hartmann K, Moses A J, Meydan T 2003 *J. Magn. Magn. Mater.* **254-255** 318.
[4] Anglada-Rivera J, Padovese L R, Capo-Sanchez J 2001 *J. Magn. Magn. Mater.* **231** 299
[5] Sablik M J, Augustyniak B, de Campos M F, Landgraf F J G 2008 *IEEE Trans. Magn.* **Mag-44** 3221.
[6] Krause T W, Szpunar J A, Atherton D L 2003 *IEEE Trans. Magn.* **Mag-39** 562
[7] Castro N A, de Campos M F, Landgraf F J G 2006 *J. Magn. Magn. Mater.* **304** e617
[8] Moses A J, Patel H V, Williams P I 2006 *J.of Electrical Eng.* **55** No 8/S 3.
[9] Chikazumi S 1964 *Physics of magnetism* John Wiley & Sons, New York.
[10] Ushigami Y, Mizokami M, Fujikura M, Kubota T, Fujii H, Murakami K 2003 *J. Magn. Magn. Mater.* **254–255** 307.
[11] Sato K, Ishida M, Hina E 1998 *Kawasaki Steel Technical Report* **39** 21.
[12] Landgraf F J G, de Campos M F, Leicht J 2008 *J. Magn. Magn. Mater.* **320** 2494.
[13] Hwang D G, Kim C G, Lee K H, Kim H C 1993 *J. Magn. Magn. Mater.* **125** 129.
[14] Alessandro B, Beatrice C, Bertotti G, Montorsi A 1990 *J. Appl. Phys.* **68** 2901.
[15] L F T Costa, F Girotto, R Baiotto, G Gerhardt, M F de Campos, F P Missell. Presented at the JEMS 2010 conference, Krakow, Poland. Journal of Physics Conference Series.
[16] M F de Campos, F A Franco, R Santos, F S da Silva, S B Ribeiro, J F C Lins, L R Padovese. Presented at the JEMS 2010 conference, Krakow, Poland. Journal of Physics Conference Series.