Structural and magnetism local studies of iron alloys with silicon contents of 3 to 10%

Samuel P. Lima[a], Thamara C. de A. C. Moreira[a], Bruno H. G. Assis[a], Daniel L. Rocco[a]

[a] *Centro Federal de Educação Tecnológica de Minas Gerais – CEFET-MG, Brasil.*

Fe-Si electrical steel is a fundamental component for electric motors and power transformers. One of the main sources of energy loss in electric motors comes from induction currents generated in the electrical steel due to the presence of a magnetic field that varies in time. This loss can be mitigated by doping the material with elements that increase its electrical resistivity, with Si being one of the widely used elements. In this work, a commercial non-oriented grain electrical steel was melted in an electric arc furnace with Si percentages ranging from 3 % to 10wt%. The focus was to study the stabilization thresholds of the crystallographic phases B2 and DO3 of the cubic structure. In addition, using Mossbauer spectroscopy and X-ray magnetic circular dichroism (XMCD) at the Fe edge, we intend to answer the following questions, respectively: a) does the decrease in saturation magnetization come from the increased presence of the non-magnetic element Si, or from the decrease in the magnetic moment of Fe at some specific crystallographic site of Fe? and b) does the increase in resistivity, which is a decrease in electron mobility, induce some orbital magnetic moment L in the Fe atoms?

Keywords: High-silicon alloys; Magnetic properties; Crystal structure, Magnetic Losses.

1. Introduction

Electrical steels are magnetic materials used to intensify magnetic fields in transformer cores and electric motors The energetic efficiency of these steels is quantified by the magnetic loss. According to Bertotti's phenomenological model [1] the total magnetic loss is the sum of the hysteresis, classical and anomalous loss. The classical loss is inversely proportional to the electrical resistivity, that is regulated in some steel by the insertion of atoms such as Si. As the Si concentration increases, an atomic ordering begins to occur, so that above 5.3 wt% the material begins to present a structure of the CsCl AB type (B2 phase), and above 6 wt% a structure of the AlFe3 type (DO3 phase) appears [2]. In fact, there is no consensus in the literature about the exact Si concentration where one phase begins and the other ends [3], [4]. The magnetic properties also depend greatly on the amount of Si; saturation magnetization decreases [2] with the Si content and magnetostriction appears to increase up to 6% Si. Thus, we used a commercial electrical steel with 2% Si and melted the material in an arc furnace with different Si concentrations up to 10%. The magnetic losses of the electrical steel (before melting) were determined in an Epstein frame. The buttons obtained after melting are being studied by X-ray diffraction with Rietveld refinement, and with local techniques such as Mössbauer spectroscopy, in order to verify the magnetic moment of the Fe atoms in the different crystallographic phases that are established with the increase of Si.

2. Results and discussion

The commercial non-oriented grain electrical steel with 2% Si was magnetically characterized prior to arc furnace melting. Figure 1 (left) shows the hysteresis curves at maximum inductions of 0.1, 0.5, 0.9 and 1.5 T at a frequency of 60 Hz. The expected increase in the area of hysteresis curve with the induction is clearly observed. Even at inductions of 1.5 T, no tendency towards saturation of the material was observed. From the hysteresis curves it was possible to determine the total losses at various maximum inductions for frequencies of 10, 12, 14, 16, 18, 20, 60 and 100 Hz. The loss values as a function of frequency are shown in Fig. 1 (right). The expected increase in total loss with frequency can be clearly seen. The values obtained are consistent with a similar material already studied by Alvim *et al.* [5].

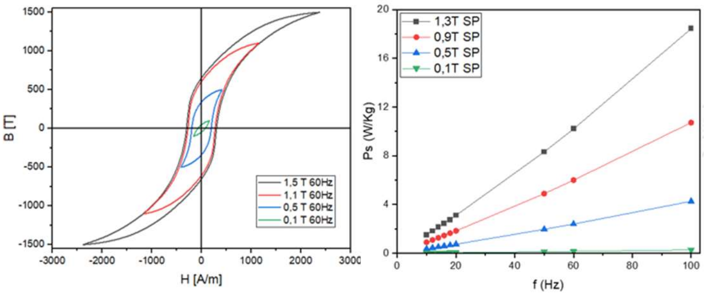

Figura 1 (left) - Hysteresis curves for 1.5, 1.1, 0.5 and 0.1 T at 60Hz; (right) - Total loss as a function of frequency for different values of maximum induction.

Using the total loss curve at low frequencies (10 to 20 Hz), it was possible to determine the hysteresis loss (Ph) by extrapolation (f ->0), and then the values of the classical loss (Pc) and the anomalous loss (Pa) could be found. Ph is the largest of all (not shown here) in the entire frequency range and for all inductions. Pc and Pa have similar values at low frequencies, but Pc becomes larger above 20 Hz due to its quadratic dependence on frequency.

The samples melted in an arc furnace are already being analyzed by X-ray diffraction with Rietveld refinement, by Mossbauer spectroscopy and a time in the SIRIUS (Brazilian particle accelerator) line has already been requested for the X-ray circular magnetic dichroism (XMCD) measurements. With these characterizations we intend to identify: a) the Si concentration where the B2 and DO3 phases exist, b) how the magnetic moment of Fe of each site of the structure evolves with Si, and thus understand the role of Si in the decrease of the saturation magnetization, and finally c) discover if there is any orbital contribution Lto the total magnetic moment of the Fe atoms.

References

[1] G. Bertotti, *IEEE Trans Magn*, vol. 24, no. 1, pp. 621–630, 1988.
[2] G. Ouyang, *et al.*', *J Magn Magn Mater*, vol. 481, pp. 234–250, 2019.
[3] T. Ros, *et al., J Magn Magn Mater*, pp. 208–211, 2002.
[4] D. Ruiz, *et al*., *Physica B Condens Matter*, v. 385-386,p. 578 580, 2006.
[5] M. Barbosa Alvim, *et al*., *Steel Res Int*, vol. 96, no. 1, Jan. 2025,

Acknowledgements: The authors would like to thank the Brazilian research funding agencies: CNPq, CAPES and FAPEMIG.