Non-destructive test to detect magnetic anisotropy

Edgard M. Silva [1], Louise G. Lima [1], Rayssa S. A. T, Lins[1], Walter M. L. Fialho[1], Alysson M. R. P. Leite[1] , João P. Leite[2], Mickael M. R. Silva[2], Josinaldo P. Leite[2]

[1] Instituto Federal da Paraíba- IFPB; edgard@ifpb.edu.br, louisegomes@gmail.com, rayssa_sara@hotmail.com, wmlfialho@gmail.com, rufinoalysson@gmail.com

[2] Universidade Federal da Paraíba, UFPB; joao.leite100@yahoo.com.br, mickaelmrodrigues@gmail.com,josinaldo@ct.ufpb.br

Abstract: A deeper understanding of materials characterization under rotational magnetization conditions phenomena enables the engineers to optimize the overall volume, mass and performance of devices of electrical machines in industry. These directions can be obtained through destructives tests as the Epstein frame method and the Single Sheet Tester (SST) measurements in the irreversible domains region of the magnetization. At the present work, a proposed system is applied to the experimental evaluation of magnetic anisotropy in steels. The proposed approach is considered non-destructive and showed to be able to determine the easy directions. Samples of rolled SAF 2205 steel are submitted to an induced magnetic field in the reversibility region of magnetic domains, to detect the easy magnetic direction. These magnetic fields were applied to circular samples which have different thickness and the application angle varied from 0° to 360° with step of 45.

Keywords: non-destructive test; magnetic anisotropy; device.

1. INTRODUCTION

The magnetic behavior of most commercial ferromagnetic steels is usually anisotropic presenting a magnetic easy axis. Changes in the direction of this axis are related to mechanical changes and anomalies that occur in the fabrication process. Some works proper new nondestructive techniques based on measurements of magnetic Barkhausen noise (MBN) signals to determine the direction of the macroscopic magnetic easy axis [1]–[7] . They also offer the possibility of obtaining real-time parameters that quantify the magnetic anisotropy of the sample [2], [8]–[11].

An Epstein frame or Epstein square is a standardized measurement device for measuring the magnetic properties of magnetic materials, especially used for testing of electrical steels [12]–

[14] . In the case of transformer steel sheets industrial the Epstein frame method is used based on destructive batch tests. Epstein frame method and the Single Sheet Tester (SST) measurements result in averaged magnetic parameters of tested steel [8], [9], [12]–[15]. Therefore, they are not proper tools to investigate local magnetic properties. The main idea of the method discussed in this work is to obtain local magnetic anisotropy from magnetic field measurement to obtain magnetic and microstructural anisotropy.

The proposed testing approach is nondestructive, not affected by samples' geometry, easy measurement and interpretation and can measure local macroscopy easy direction in areas of 4.5 cm^2. Epstein and Small single sheet testers (SST) use specimens areas from 84 to 93 cm^2, and 25 cm^2 to 1296 cm^2, respectively and they are destructive tests. Others technique applied are based in the Barkhousen noise signals the dimension of the samples used for the same purpose are from 50,4 cm^2 to 100 cm^2 [2], [7]–[9], [12]–[14].

In this study, induced magnetic field measurements obtained by direct current in the reversibility region of magnetic domains are used to study anisotropy in rolling steel. An as-received rolled SAF 2205 steel was used in this studied. The objective was to propose a nondestructive testing approach to detect local magnetic anisotropy in steels.

2. METODOLOGY

As-received rolled SAF 2205 steel samples having 24 mm diameter and 2, 4, 6, 8 mm thickness were submitted to a magnetic field of 188 A/m. The measures were taken at the center of the sample. The measures were executed at the following angles: 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°, 360°. The studied surface was perpendicular to the rolling direction.

The as-received rolled and annealed SAE 1045 steel samples were submitted to metallographic, which allowed studying their microstructure. Its surfaces were attacked using the Behara reagent and analyzed through optical microscopy (FX 35XD NIKON Optic Microscopy, Germany) which has image acquisition system.

The experimental setup showed in Figure 1 was used to study the samples under analysis based on the application and assessment of induced fields. In this setup, a solenoid is responsible for generating the external magnetic field, and a Hall Effect sensor (from Honeywell, USA, model SS495A) is used to determine the magnetic flux density. The Hall effect integrated circuit chip provides increased temperature stability and sensitivity. Laser trimmed thin film resistors on the chip provide high accuracy (null to ±3%, sensitivity up to ±3%) and temperature compensation to reduce null and gain shift over temperature. The quad Hall sensing element minimizes the effects of mechanical or thermal stress on the output. The positive temperature coefficient of the sensitivity (+0.02%/°C typical) helps compensate for the negative temperature coefficients of low cost magnets, providing a robust design over a wide temperature range. The SS495A sensor is provides calibrated. External magnetic fields up to 188 A/m were applied to generate the induced fields in the region of reversibility of the magnetic domain. The external magnetic field was produced by direct current. Five hundred signals were acquired from each sample and measurements were obtained with confidence intervals of 95%.

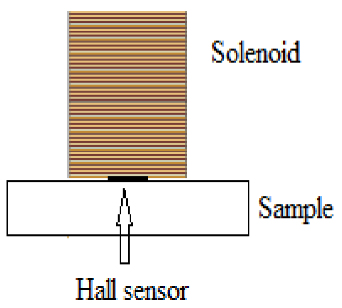


Fig. 1. Position of the sensor.

3. RESULTS AND DISCUSSION

The microstructure of the stainless steel as-received is showed in Figure 2, where can be observed the ferrite phase (α) and elongated grains of autenite (γ) one, due to rolling..

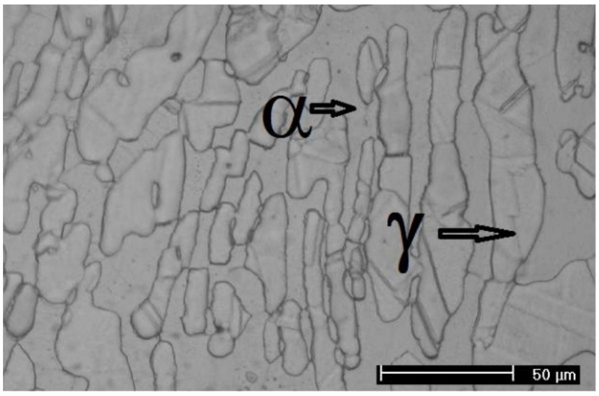
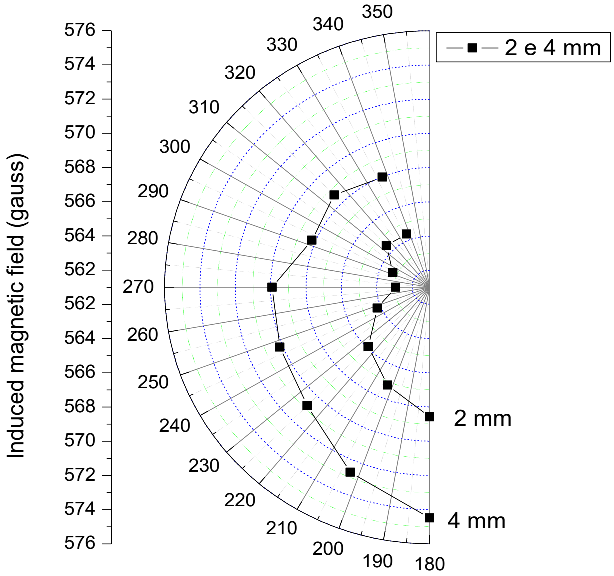


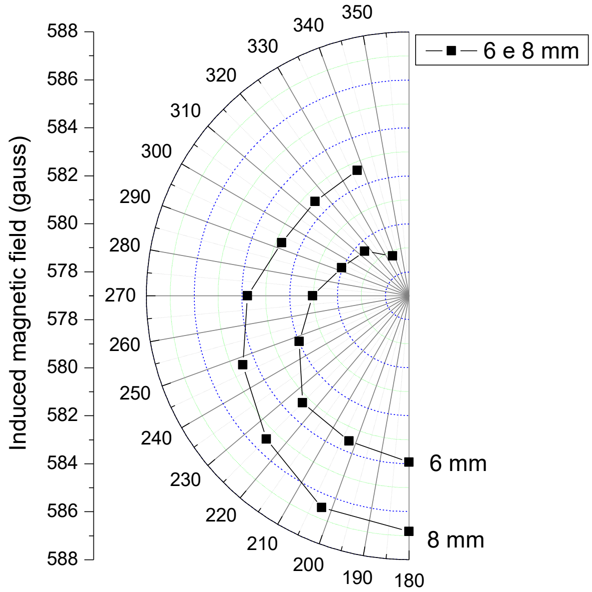
Fig. 2. The microstructure of the stainless steel as-received, where α is the ferrite phase and γ the austenite one.

This work tried to observe the magnetic anisotropy of the steel here studied. Several studies were developed for this purpose, but some used destructive tests and others nondestructive test but with specimens of higher dimensions as compared with the ones of the present work, as already showed [2]–[4], [7], [12], [16]. They have shown that magnetic properties of ferromagnetic materials suffer interference from the microstructure and from the stress conditions which come from the plastic deformation. This is caused by the conventional manufacturing processes, leading to an anisotropic behavior of the variables just mentioned[13], [14], [17]–[19].

The procedure used to study the magnetic anisotropy consisted of measuring at the center of the samples rotating them from 0º to 360º. The behavior obtained to the induced magnetic field as a function of the rotation angle can be seen in the Figures 3. The material used in all the samples was the same; so there was no alteration of the material permeability. The external magnetic field value was kept constant.



a) 2 e 4 mm.



b) 6 e 8 mm.

Fig. 3. Induced magnetic field in function of the rotated angle. a) 2 e 4 mm. b) 6 e 8 mm.

The relation between the induced magnetic field (B) and the incidence angle, presented in the Figures 3, shows an anisotropic behavior because it changes according to the variation of the sample position about the incident magnetic field and also to the sample rotation. Others studies detected the change in the B value due to the rotation angle too, indicating that magnetization curves suffer interference from the plastic deformation, which causes magnetic anisotropy [2], [7], [13]–[15], [10].

Figure 3 shows that the measures carried out in the center show the easy direction in the rolling one (180º). This can be noted both in the measurements made in all samples. The results show that the 180 ° angle corresponds to the easy magnetization due to the higher values of induced fields obtained. This means that the magnetic losses are lower in this direction. The present work is performed with direct current and fixed pole, and if the pole is changed the polar graph will show larger values of induced magnetic field around the angle of 0 °. The angles of 0 ° and 180 ° correspond to opposite sense in the same direction of easy magnetization. Martinez (2015) showed the formation of polar curves in the form of eight to materials with rolled microstructure[10][8], [9]. Martinez used alternating current instead of direct one. Martinez associates eight form due to the displacement of the magnetic domains walls. In the reversibility region occur movements of the domains walls, however reversibly.

Emura 2001 et al. studied the magnetic induction fields to applied external ones values of 2500 A/m (B_{25}) and 5000 A/m (B_{50}), as a function of the angle rotated from the rolling direction of a non-oriented 2% Si steel [12]. They found a minimum at 54º indicating a texture more unfavorable to magnetization in this direction than parallel and perpendicular to rolling. Landgraf et al. also observed in non-oriented steels the presence of the worst magnetic properties between the angles 45 to 60º for a steel with 3.25%Si and the best in the rolling direction [13], [14].

Standard based tests to anisotropy analysis are accomplished to determine the magnetic angle in which there is low loss. For that it is necessary to apply magnetic fields in the region of high induction loss of the hysteresis loop, which is enough to promote irreversible modification in the magnetic domains positions in the material. These tests need to remove specific samples of the materials and so they are destructive tests[1]–[7], [12], [16], [17]. The experiment made in this work has shown that applying a low intensity of magnetic field allows obtaining the easier magnetization direction of the material without needing to remove samples to study, this means it is a non-destructive test.

4. CONCLUSIONS

The present work studied a non-destructive test to detect magnetic anisotropy getting the following conclusions:

The results presented here show that the technique is able to determine the direction of easy magnetization of the studied steel, regardless of the samples geometry. It was also able to detect the microstructural anisotropy that was responsible for the magnetic one of the material. The higher induced magnetic field was detected in angle of 180 °, which is the rolling direction.

5. REFERENCES

[1] A. Bükki-Deme, I. A. Szabó, and C. Cserháti, “Effect of anisotropic microstructure on magnetic Barkhausen noise in cold rolled low carbon steel,” *J. Magn. Magn. Mater.*, vol. 322, no. 13, pp. 1748–1751, 2010.

[2] M. Caldas-Morgan and L. R. Padovese, “Fast detection of the magnetic easy axis on steel sheet using the continuous rotational Barkhausen method,” *NDT E Int.*, vol. 45, no. 1, pp. 148–155, 2012.

[3] J. Capó-Sánchez, M. Alberteris Campos, and L. R. Padovese, “Magnetic Barkhausen measurements for evaluating the formation of

Lüders bands in carbon steel," *NDT E Int.*, vol. 40, pp. 520–524, 2007.

[4] J. Capó-Sánchez, J. Pérez-Benitez, and L. R. Padovese, "Analysis of the stress dependent magnetic easy axis in ASTM 36 steel by the magnetic Barkhausen noise," *NDT E Int.*, vol. 40, no. 2, pp. 168–172, 2007.

[5] S. Chen, J. Butler, and S. Melzer, "Effect of asymmetric hot rolling on texture, microstructure and magnetic properties in a non-grain oriented electrical steel," *J. Magn. Magn. Mater.*, vol. 368, pp. 342–352, 2014.

[6] Y. P. Chernenkov, N. V Ershov, V. A. Lukshina, V. I. Fedorov, and B. K. Sokolov, "An X-ray diffraction study of the short-range ordering in the soft-magnetic Fe-Si alloys with induced magnetic anisotropy," *Phys. B-Condensed Matter*, vol. 396, no. 1–2, pp. 220–230, 2007.

[7] L. Clapham, C. Heald, T. W. Krause, D. L. Atherton, and P. Clark, "Origin of a magnetic easy axis in pipeline steel," *J. Appl. Phys.*, vol. 86, no. 3, pp. 1574–1580, 1999.

[8] P. Martínez-Ortiz, J. A. Pérez-Benítez, J. H. Espina-Hernández, F. Caleyo, and J. M. Hallen, "On the estimation of the magnetic easy axis in pipeline steels using magnetic Barkhausen noise," *J. Magn. Magn. Mater.*, vol. 374, pp. 67–74, 2015.

[9] P. Martínez-Ortiz, J. A. Pérez-Benítez, J. H. Espina-Hernández, F. Caleyo, N. Mehboob, R. Grössinger, and J. M. Hallen, "Influence of the maximum applied magnetic field on the angular dependence of Magnetic Barkhausen Noise in API5L steels," *J. Magn. Magn. Mater.*, vol. 401, pp. 108–115, 2016.

[10] J. a. Pérez-Benitez, J. Capó-Sánchez, and L. R. Padovese, "Characterization of angular dependence of macroscopic magnetic properties in ASTM 36 steel using magnetic Barkhausen noise," *NDT E Int.*, vol. 40, pp. 284–288, 2007.

[11] R. Skomski and J. M. D. Coey, "Magnetic anisotropy — How much is enough for a permanent magnet?," *Scr. Mater.*, 2015.

[12] M. Emura, M. F. de Campos, F. J. G. Landgraf, and J. C. Teixeira, "Angular dependence of magnetic properties of 2% silicon electrical steel," *J. Magn. Magn. Mater.*, vol. 226–230, pp. 1524–1526, 2001.

[13] F. J. G. Landgraf, T. Yonamine, M. Emura, and M. A. Cunha, "Modelling the angular dependence of magnetic properties of a fully processed non-oriented electrical steel," *J. Magn. Magn. Mater.*, vol. 254, pp. 328–330, 2003.

[14] F. J. G. Landgraf, M. Emura, J. C. Teixeira, M. F. De Campos, and C. S. Muranaka, "Anisotropy of the magnetic losses components in semi-processed electrical steels," *J. Magn. Magn. Mater.*, vol. 196, no. May, pp. 380–381, 1999.

[15] K. M. Marra, E. a. Alvarenga, and V. T. L. Buono, "Magnetic aging a nisotropy of a semi-processed non-oriented electrical steel," *Mater. Sci. Eng. A*, vol. 390, no. 1–2, pp. 423–426, 2005.

[16] M. Elmassalami, I. Palatnik-De-Sousa, M. C. L. Areiza, J. M. a Rebello, and a. Elzubair, "On the magnetic anisotropy of superduplex stainless steel," *J. Magn. Magn. Mater.*, vol. 323, no. 18–19, pp. 2403–2407, 2011.

[17] F. Fiorillo, "Anisotropy and magnetization process in soft magnets: Principles, experiments, applications," *J. Magn. Magn. Mater.*, vol. 304, pp. 139–144, 2006.

[18] B. Fryskowski, "Experimental evaluation of magnetic anisotropy in electrical steel sheets," *J. Magn. Magn. Mater.*, vol. 320, pp. 515–522, 2008.

[19] A. Kumar and A. Misra, "Shape anisotropy of magnetic field generation during tensile fracture in steel," *J. Magn. Magn. Mater.*, vol. 285, no. 1–2, pp. 71–78, 2005.