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NON-DESTRUCTIVE ELECTROMAGNETIC TEST FOR DETECTING DISCONTINUITIES IN STEELS

Edgard de Macedo Silva
Carlos Eduardo Bezerra Lopes
Francisco Eduardo Mendes da Silva
Ibernon Pereira de Barros Neto
Amanda Medeiros Rodrigues
Louise Gomes de Lima

Instituto Federal da Paraíba, João Pessoa, Av. primeiro de Maio 720.

edgard@ifpb.edu.br, arthuci@gmail.com, ceblopes@gmail.com, lousiegomes@gmail.com, sergioaugustosampaio@gmail.com.

Josinaldo Pereira Leite

Universidade Federal da Paraíba, Campus I, João Pessoa, Paraíba

josinaldo@ct.ufpb.br, joao.leite100@yahoo.com.br

Abstract. *Electromagnetic tests based on the interaction between magnetic flux density and material have been used to monitor the formation of microstructures that may compromise the mechanical properties and resistance to corrosion of materials. The magnetic permeability in the reversibility region of movement of the magnetic domains walls has been applied to detect phases harmful to the toughness of stainless steels. However, these tests have been used to detect cracks. In the present work, an electromagnetic test based on measurements of magnetic permeability and simulations by the Finite Element Method are used to detect the presence of discontinuities in a SAE 1045 steel. Discontinuities with 2 mm, 4 mm and 6 mm in diameter are analyzed and compared with condition without the presence of these. An experimental configuration where the sample was positioned between a Hall effect sensor and a solenoid was used. Different intensities of magnetic fields until sensor saturation were applied to the solenoid in order to detect what best detected the presence of discontinuities. The presence of discontinuity reduces the permeability of the material and shifts the magnetization curve to lower values of magnetic flux density. The electromagnetic test showed to be able to detect the discontinuity of 2 mm, which according to the quantity and concentrations are critical in structures of the oil and gas sector.*

Keywords: *discontinuities, finite element methods, permeability.*

1. INTRODUCTION

Non-destructive tests are developed to detect discontinuities that can compromise the integrity of structures in service without the need to remove samples. Among them we have ultrasound and eddy currents, magnetic particles and electromagnetic tests. In the latter, we have those based on the analysis of magnetic Barkhausen noise and permeability change. These are used to monitor the microstructure, formed by impositions of thermal cycles such as welding processes, which can compromise the mechanical properties and corrosion resistance (Ducharne et al., 2017; El Rayes et al., 2015; Silva et al., 2016a; Silva et al., 2016b; Xia et al 2016, Gur et al., 2004).

When traveling through a material, an electromagnetic wave brings information about its microstructure, either in the form of its distortions by the form of Magnetic Barkhausen Noise (MBN), or by the variation in the amplitude of the magnetic flux density resulting from changes in magnetic permeability (Miesowicz et al., 2016, Tavares et al., 2019). The application of magnetic field intensities able of overcoming anchoring points such as dislocations, precipitates, second-phase particles and grain boundaries generate the MBN and thus characterize the region of irreversibility of the movement of the magnetic domains walls. However, when they cannot overcome, we will be in the region of magnetic reversibility and when we stop applying the external field, the material returns to its initial state (Silva et al., 2016a; Silva et al., 2016b).

Formation of nanostructures such as α' and coarse precipitates such as sigma, which impair the toughness of duplex stainless steels, have been studied in both the reversibility and irreversibility regions of magnetic domain wall motion. The first changes the permeability by blocking domain movements and the second changes because the sigma phase is a paramagnetic microstructure (Silva et al., 2016a; Silva et al., 2016b). These type of microstructures were also studied

by ultrasound testing through sonic velocity measurements (Normando et al., 2010; De Albuquerque et al., 2009, Silva et al 2016c).

The presence of discontinuities such as voids, porosities and cracks change the permeability of the material and thus can modify the interaction between magnetic flux density and material. Thus, in the present work the presence of 2 mm, 4 mm and 6 mm discontinuities are studied in a SAE 1045 steel through permeability change in the magnetic reversibility region and by the Finite Element Method.

2. METHODOLOGY

In this work, an inspection was made to detect discontinuities in ferromagnetic materials. For this, four samples of a SAE 1045 steel were made according to Figure 1, three with holes of 2 mm, 4 mm and 6 mm in diameter, which represented discontinuities. These are rectangular specimens with a length of 63 mm and width and height of 9 mm. The fourth sample represents the condition without discontinuity that is without a hole. The samples were wet machined in order to avoid heating that could cause microstructural changes. Measurements were taken in the center of the sample where the discontinuity is located and 16 mm from the center of the sample to the left and right, respectively.

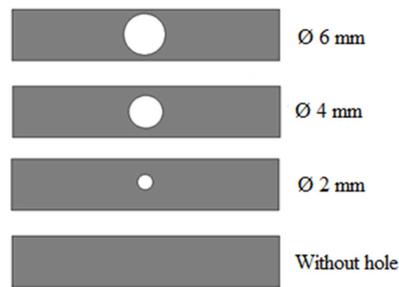


Figure 1. Scheme of experimental samples.

The electromagnetic test employed consisted in the application of different magnetic field intensities, through a coil, in the samples to be analyzed, and detection of the magnetic flux density resulting from the interaction through a Hall Effect sensor positioned on the opposite surface of the coil. The applied magnetic field strengths were carried out until sensor saturation. This configuration is shown in Figure 2.

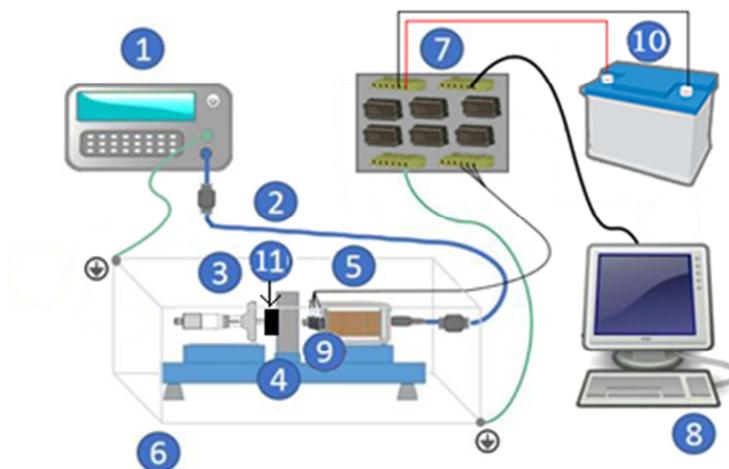


Figure 2. Experimental bench for the magnetic permeability test: (1) Direct Current Source; (2) Shielded Cable; (3) Micrometer for sample adjustment; (4) Sample; (5) Induction coil; (6) Faraday's Cage; (7) Data acquisition board; (8) Computer; (9) Bench base (10) 12v dc battery (11) Hall Effect sensor.

The acquisition module integrates a Hall Effect sensor, a data acquisition board, a 12v battery and a computer and a coil. The samples were positioned between the Hall sensor and the coil. The sensor was used in order to detect the

magnetic flux density generated by the coil and transmit the signal to a data acquisition board responsible for converting the analog signal into digital. The computer received the digital signal from the data acquisition board via USB cable and performed automatic data acquisition using the program developed in the laboratory. The sensor used was a Honeywell brand, model SS495A. The resulting magnetic flux density in the reversibility region is proportional to the magnetic permeability of the material under study. This means that the resulting magnetic flux density obtained is not affected by changes in sample geometry. Five hundred signals were acquired from each point of measurement and magnetic flux density values were obtained with a 95% confidence interval. A Faraday cage and shielded cables were used in order to reduce the interference of signals coming from the environment.

The bench was simulated by the Finite Element Method in order to analyze the interaction between the magnetic flux density and the studied material.

3. RESULTS AND DISCUSSIONS

Figure 3 shows the magnetic flux density as a function of the voltage applied to the coil for samples with a 2 mm hole and without discontinuity. Measurements were performed in the center of the samples. A linear behavior in the measurements can be seen in Figure 3, following a saturation level. This is due to Hall Effect sensor saturation. Linearity is characteristic of the magnetic reversibility region of the movement of the magnetic domains walls, where the tangent corresponds to the magnetic permeability of the material. The results of measurements performed on samples with holes showed lower values of magnetic flux density. This is because the presence of air in the discontinuity reduces the magnetic permeability at the measurement position, indicating the presence of the discontinuity (Silva et al 2016a, Silva et al 2016b).

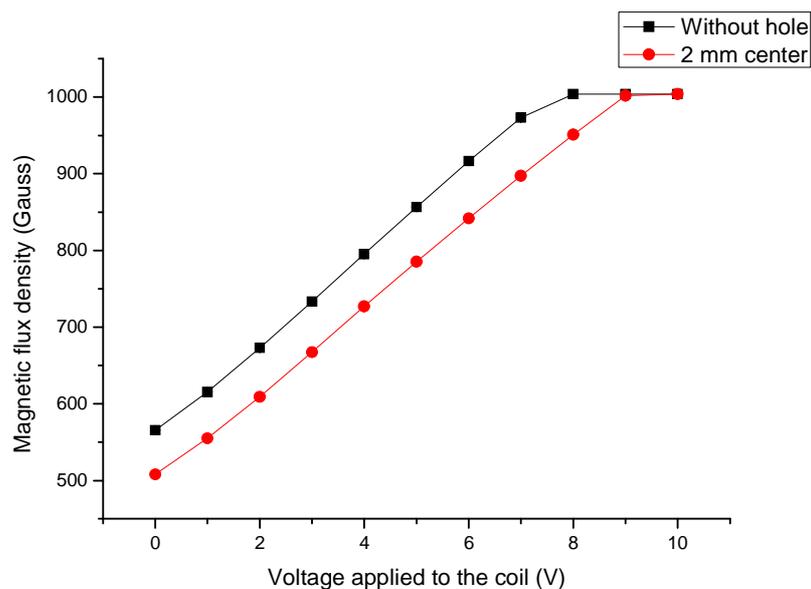


Figure 3. Variation of magnetic flux density as a function of voltage applied to the coil, for conditions with and without the presence of a 2 mm discontinuity.

In order to determine the optimal measurement condition, the greatest difference between the conditions with and without the presence of discontinuities was determined for the conditions with 2 mm, 4 mm and 6 mm. This is shown in Figure 4. In this one, the same behavior is observed for the three discontinuities, with the conditions with 4 mm and 6 mm presenting similar values. The peak observed in Figure 4 is due to the approximation of the sensor's saturation point. It can be seen that the point of greatest difference corresponds to the application of a voltage of 7 V on the coil, that is, the optimal condition that results in the greatest measurement amplitude. This was chosen for the 2mm discontinuity analysis with measurements both in the center of the samples and offset by 16mm to the left and right of the sample.

An important point in Figure 4 that is worth noting is that the sample in which the measurements were taken is 9 mm wide by 9 mm high and one of the discontinuities is 6 mm in diameter made in the center of the sample, that is, 1 remains, 5 mm of material thickness to reach the surface, this type of discontinuity is limited to be detected by ultrasound due to the limitation of the width of the ultrasonic beam, generating a region in which is difficult to detect

faults, known as the dead zone. Therefore, if there is a discontinuity present in the dead zone, it will not be detected, compromising the reliability of the inspection (KIRCHHOF et al., 2017).

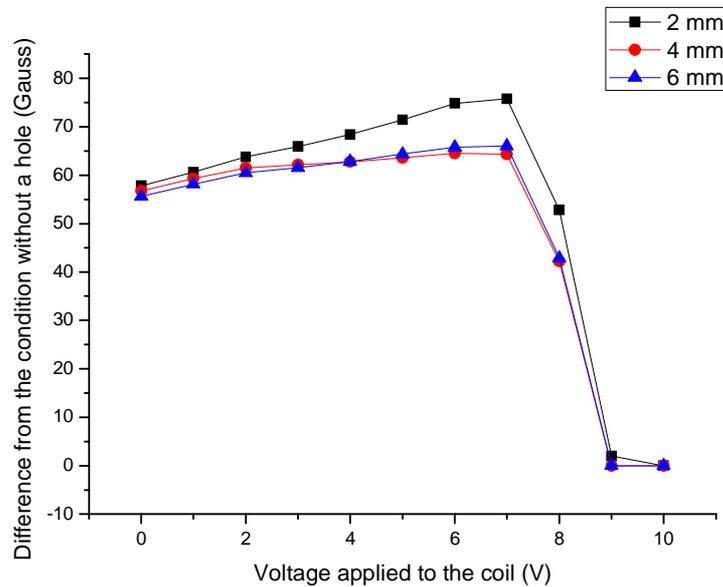


Figure 4. Difference in magnetic flux density between conditions with 2 mm discontinuities. 4 mm and 6 mm, in relation to the sample without a hole.

Figure 5 shows the magnetic flux density measurements between the conditions with and without the 2mm discontinuity, for the center, left and right positions. There is a difference of around 90 Gauss between the two conditions for the three measurement positions, indicating the presence of discontinuity in the material.

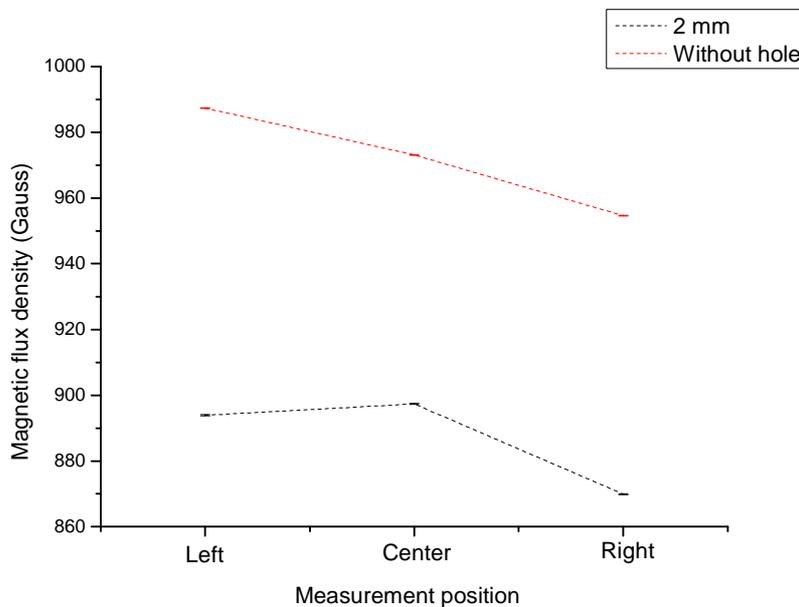


Figure 5. Sample magnetic flux density with discontinuity of 2 mm and without the presence, for measurements in the center, right and left of center, with application of a voltage in the coil of 7 V.

The interaction between the magnetic flux density and material was simulated by the Finite Element Method. Figures 6a and 6b show the simulations for conditions with and without the presence of discontinuities. The holeless condition in Figure 6a shows the magnetic flux passing through the material thickness. On the opposite surface of the

coil, together with the sensor, a magnetic field concentrator was placed so that the flux would overcome the thickness and reach the sensor. The simulation showed the need to use a ferromagnetic solid with the sensor to perform the flux concentration.

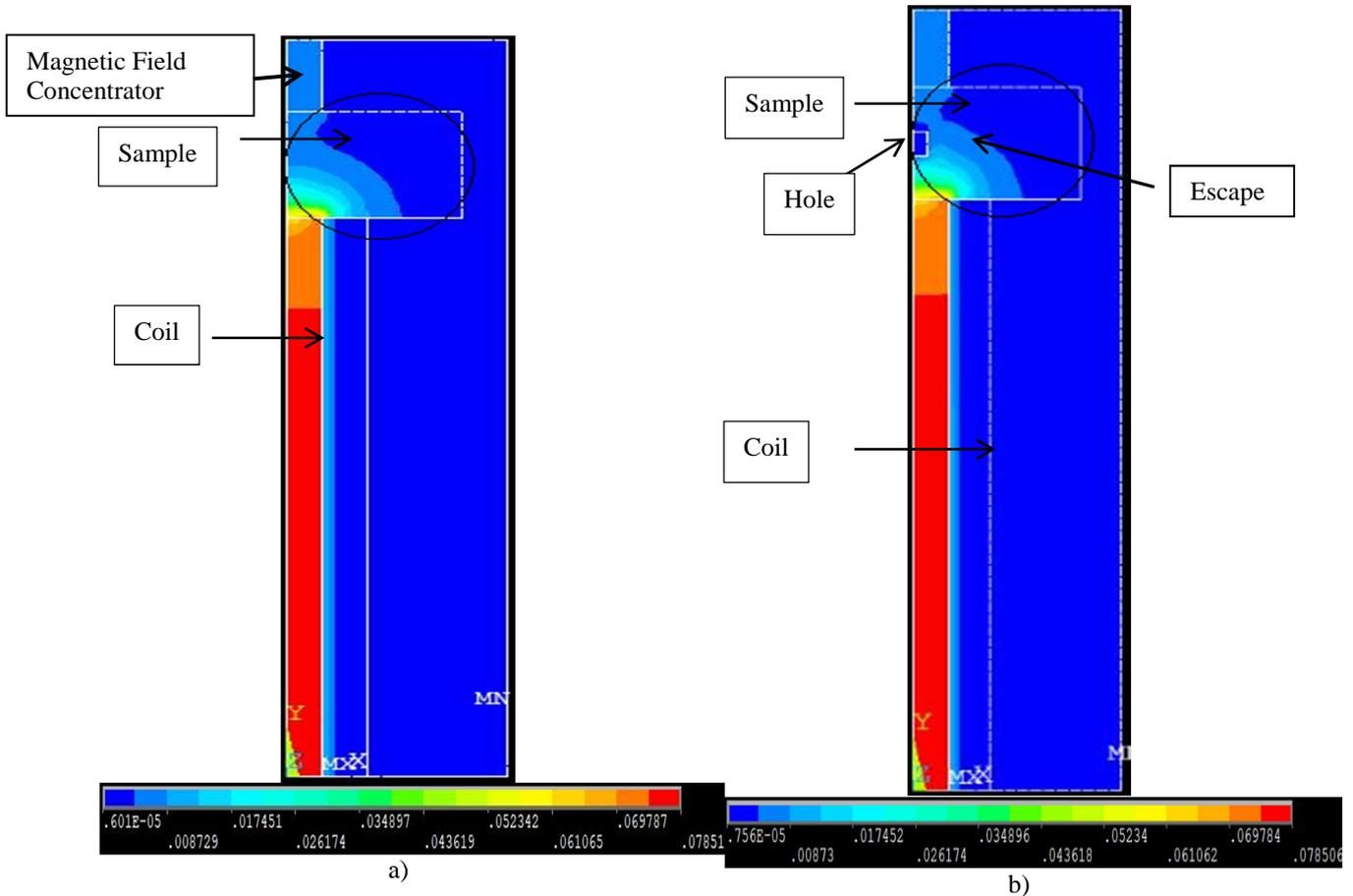


Figure 6. Finite Element Method simulation of the holeless condition.

Figure 6b shows the simulation for the sample with a 2 mm hole. It is observed that there is a leakage of the magnetic flux density inside the material, leading to a decrease in the intensity of the magnetic flux density that arrives on the opposite side of the sample. Discontinuities change the permeability of the material and change the amount of flux in the sensor region. From the experiments and simulations using the Finite Element Method, we can see that the technique is able to detect discontinuities and serving as a complementary technique to ultrasound in the dead zone region.

4. CONCLUSIONS

The present work presents a non-destructive electromagnetic test for detecting discontinuities in steel. A SAE 1045 steel with and without the presence of discontinuities was analyzed through changes in its permeability reaching the following conclusions:

- i. The experiments show that there is an optimal condition to obtain a greater measurement amplitude in the studied electromagnetic test, which for the conditions was 7 V, that is, before the sensor saturation.
- ii. Simulation by the Finite Element Method (FEM) is able to simulate the test bench and facilitate the understanding of the interaction of the magnetic flux density with the material for different permeabilities.
- iii. The proposed electromagnetic test was able to detect discontinuities of 2 and 6 mm, through measurements of magnetic flux density, in addition to detecting the presence of discontinuities at 1.5 mm from the surface. This is intended as a complementary test to the ultrasound technique, as it can be used to detect defects in the dead zone of this technique.

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6. REFERENCES

- Ducharne, B., Le, M. Q., Sebald, G., Cottinet, P. J., Guyomar, D., and Hebrard, Y., 2017. "Characterization and modeling of magnetic domain wall dynamics using reconstituted hysteresis loops from Barkhausen noise", *J. Magn. Mater.*, Vol. 432, pp. 231–238.
- De Albuquerque, V. H. C., SILVA, E. M., Pereira, L. J.; de Moura, E. P.; de Araújo Freitas, V. L., Tavares, J. M. R.S., 2010. "Spinodal decomposition mechanism study on the duplex stainless steel UNS S31803 using ultrasonic speed measurements". *Materials in Engineering (Cessou em 1982. Cont. ISSN 0264-1275 Materials and Design)*, Vol. 31, pp. 2147-2150.
- El Rayes, Magdy, M., El-Danaf, Ehab A., Almajdi, Abdulhakim A., 2015. "Ultrasonic characterization of heat-treatment effects on SAE-1040 and 4340 steels". *Journal of Materials Processing Technology*. Vol. 216, pp. 188–198.
- Gur, C. H. and Tuncer, B. O., 2014. "Investigating the microstructure-ultrasonic property relationships in steels". 16th WCNDT-World Conference on NDT, 2004.
- Kirchhof, J., Krieg, F., Romer, F., Ihlow, A., Osman, A. and GALDO, G. D., 2017. "Sparse Signal Recovery for ultrasonic detection and reconstruction of shadowed flaws". *Acoustics Speech and Signal Processing (ICASSP) 2017 IEEE International Conference on*, pp. 816-820, 2017.
- Miesowicz, K., Staszewski, W. J., and Korbiel, T., 2016. "Analysis of Barkhausen noise using wavelet-based fractal signal processing for fatigue crack detection". *Int. J. Fatigue*. Vol. 83, pp. 109–116.
- Normando, P. G., Moura, E. P., Souza, J. A., Tavares, S. S. M., and Padovese, L. R., 2010. "Ultrasound, eddy current and magnetic Barkhausen noise as tools for sigma phase detection on a UNS S31803 duplex stainless steel", *Mater. Sci. Eng. A*, Vol. 527, No. 12, pp. 2886–2891.
- Silva, E. de Macedo, Leite, J. P., Neto, F. A. de França, Leite, J. P., Fialho, W. M. L., Albuquerque, V. H. C. and Tavares, J. M. R. S., 2016a. "Evaluation of the Magnetic Permeability for the Microstructural Characterization of a Duplex Stainless Steel". *J. Test. Eval.* Vol. 44, No. 3, p. 20130313.
- Silva, E. M., Paula, A. M. R., Leite, J. P., Leite, J. P., Andrade, L. S. S., Albuquerque, V. H. C. and Tavares, J. M. R. S., 2016b. "Detection of the Magnetic Easy Direction in Steels Using Induced Magnetic Fields". *Metals - Open Access Metallurgy Journal*, Vol. 6, No. 12, p. 317.
- Silva, E. M., Fialho, W.M.L., Silva, H.F.B.M., Leite, J.P., Oliveira, A. V. G., 2016c. "Sigma phase detection in duplex stainless steel by induced magnetic field". *Journal of Physics. Conference Series (Print)*. Vol. 733, pp. 012070.
- Tavares, S. S. M., Noris, L. F., Pardal, Da Silva M, J. M., 2019. "Temper embrittlement of supermartensitic stainless steel and non-destructive inspection by magnetic Barkhausen noise". *Engineering Failure Analysis*, Vol. 100, pp. 322 – 328.
- Xia, D.-H., Song and S.-Z. Behnamian. Y., 2016. "Detection of corrosion degradation using electrochemical noise (EN): review of signal processing methods for identifying corrosion forms". *Corros. Eng. Sci. Technol.* Vol. 51, No. 7, pp. 1–18.

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