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# MAGNETIC PERMEABILITY MEASURES FOR THE DETECTION OF HEAT TREATMENTS AND ANISOTROPY IN A SAE 4340 STEEL

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*Abstract. In the present work, an electromagnetic test based on the application of field intensities in the region of magnetic reversibility is applied to detect the effect of heat treatments on a SAE 4340 steel, which has a high depth hardening capacity and has a wide application in the industry, such as in aerospace where it is used in aircraft landing gear. Four different heat treatments: an annealing at a temperature of 850 ºC, austenitization at 1000 ºC followed by cooling in the oven, in oil and in water were analyzed and compared with the condition as received from the material under study. A fixed magnetic field intensity was applied, in order to analyze the value of the magnetic permeability for the applied treatments. The influence of treatments on the magnetic anisotropy of the steel under study was also analyzed. A fixed magnetic field strength was applied to treated circular samples, and these were rotated with steps from 45 to 360 degrees. The analysis of the obtained magnetic permeability results shows that the test is able to differentiate the treatments, being sensitive to the variation in the amount of the ferrite constituent, which is ferromagnetic, as well as the presence of the martensite structure showing that it can be correlated with hardness measures. In addition, it was possible to verify the presence of a direction of easy magnetization, regardless of the microstructure of the heat treatment employed.*

## 1. INTRODUCTION

Magnetic properties depend on various characteristics of materials such as chemical composition, microstructure, hardness, stress states, deformations and heat treatments (Miesowicz et al, 2016; Ducharne et al, 2017; Silva et al, 2016a; Xia, 2016). The material microstructures present variations due to thermal cycles and/or mechanical forming processes, which lead to changes in the material permeability and its magnetic and mechanical properties.

Electromagnetic tests have been used to monitor phases that may interfere with the mechanical properties of structures in services (Ispirli and Yilmaz, 2018; El Reys et al, 2015). The formation of new phases in ferromagnetic materials causes the change in the magnetic permeability of the one and thus can be determined by them. Tests such as parasitic currents and Barkhausen noise are used for this purpose (Ducharne et al., 2007; Miesowicz, Staszewski, and Korbiel, 2016). The magnetic Barkhausen noise is generated from the attempt of the domain walls to detach themselves from the anchor points. These can be grain boundary, second phase, precipitates and dislocations, for example. The magnetic fields used are part of the irreversibility region of the materials magnetization curve. Otherwise we have the application of intensity of magnetic fields that do not lead the magnetic domains walls to surpass the anchorage points and in this case we are working in the reversibility region and this region is also used in nondestructive electromagnetic test (Silva et al. 2016a).

By applying a magnetic field strength to a ferromagnetic material, it is possible, through a Hall sensor, to detect the permeability variation resulting from microstructural changes due to heat treatments or mechanical forming processes. These variations in microstructure have been studied by other methods and in other materials and have proven to be effective (Ispirli and Yilmaz, 2018; El Reys et al, 2015; Miesowicz, 2016). Electromagnetic tests in the region of

reversibility of the magnetic domains movement have been developed to monitor embrittlement in duplex stainless steels, by formation of new microstructures due to the imposition of thermal cycles (Silva et al. 2016a; Silva 2016b). The formation of harmful phases such as sigma and α` have been studied by permeability measurements with the application of a magnetic flux density and determination of the interaction with the material using a Hall effect sensor. In addition, they are used to detect the direction of easy magnetization in steels such as 1045 and 4340 (Silva et al. 2016a; Silva 2016b).

In the present work, an electromagnetic test applied in the region of reversibility of the magnetic domains movement was applied to detect the effect of heat treatment in a SAE 4340 steel, as well as the presence of magnetic anisotropy from the manufacturing process. This steel was chosen because it has a high hardening capacity by heat treatment and is widely used in the industry such as transmission shafts and aircraft landing gear.

## 2. METHODOLOGY

This work proposes to detect the effect of heat treatments on a SAE 4340 steel, through magnetic permeability measurements by an electromagnetic test. A SAE 4340 steel that has high hardenability and a high hardening capacity was chosen. Circular samples with  diameters of 24 mm and 5 mm thick were subjected to different heat treatments: heating at a temperature of 850 ºC for 30 min, followed by air cooling (annealing), heating at 1000 ºC for 30 min (austenitization) followed by cooling in oil, water and another in the oven. An untreated sample called "sample as received" was also used in order to make comparisons with the treatments applied to the other samples. The treatments resulted in microstructures of ferrite plus pearlite with different grain sizes (annealing and austenitizing in the oven) and martensite (quenching in oil and water). The treatments used are shown in Table 1.

Table 1. Heat treatments applied to samples.

| Samples type | Nº of samples | Applied heat treatments | Treatment time (min) |
|---|---|---|---|
| SAE 4340 Steel (Ø 24 mm x 5 mm) | 0 | As received | --- |
| | I | Annealing at 850 ºC | 30 |
| | II | Austenitization at 1000 ºC and quenched in oil | 30 |
| | III | Austenitization at 1000 ºC and quenched in water | 30 |
| | IV | Austenitization at 1000 ºC and cooled in oven | 30 |

The acquisition module integrates a Hall effect sensor, a data acquisition board, a 12v battery and a computer. The Hall sensor was placed on the same side of the coil 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 experimental setup shown in Figure 1 was used to study the samples under analysis based on the application of a magnetic field strength and evaluation of the resulting magnetic flux density. In this configuration, a solenoid is responsible for generating the external magnetic field and an effect sensor is used to determine the density of the magnetic flux. The sensor used was a Honeywell brand, model SS495A. An external magnetic field strength of 282 A/m was applied to generate the resulting magnetic flux density in the reversibility region of the magnetic domain. The reversibility region of the magnetic domains movement corresponds to the magnetization region, where the domains are randomly oriented, and the application of an external magnetic field does not cause their permanent movement or residual field. 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 by a fixed external magnetic field is not affected by changes in sample geometry. Five hundred signals were acquired from each sample 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 layout of the experimental bench can be seen in Figure 1.
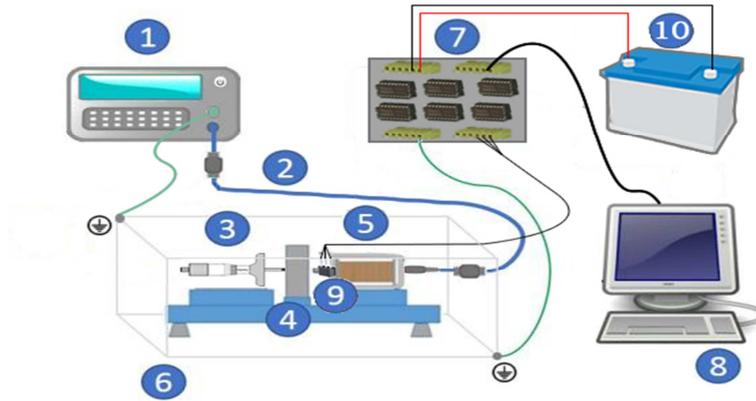
Figure 1. Experimental bench: Power Supply (1); Shielded Cable (2); Micrometer for sample adjustment (3); Sample (4); Induction coil (5); Faraday's Cage (6); Data acquisition board (7); Computer (8); Hall sensor for detection (9) and 12vdc battery (10).

Permeability measurements were determined by the ratio between the magnetic flux density measured by the Hall Effect sensor in situations with and without the presence of samples. All measurements were performed in the center of the samples. In the case of the magnetic anisotropy study, the samples were rotated from 0 to 360 degrees with a variation of 45 degrees. The specimen holder is rotated with a graduated degrees of $45^{o}$ and the specimen is manually rotated. During the rotation, a residual magnetization occurs with each new set of measurements, which, when being in the reversibility region of the magnetic domains walls movement and it tends to disappear with the realignment of the domains. However, this behavior is noted with the reduction of permeability at the angle of $360^{o}$ in relation to $0^{o}$. All measurements were performed with a 95% confidence interval.

Five Rockwell C hardness measurements were performed in each sample in order to correlate with the magnetic permeability.

## 3. RESULTS AND DISCUSSIONS

Figure 2 shows the measurements of magnetic permeability found as a function of the heat treatment performed and its absence of treatment for the case of the sample as received. From Figure 2, an increase in magnetic permeability values for the sample annealed at 850 °C can be seen in comparison to the sample as received and it is followed by a decay due to the treatments applied to it, which are austenitization at 1000 °C followed by cooling to oven, oil and water.
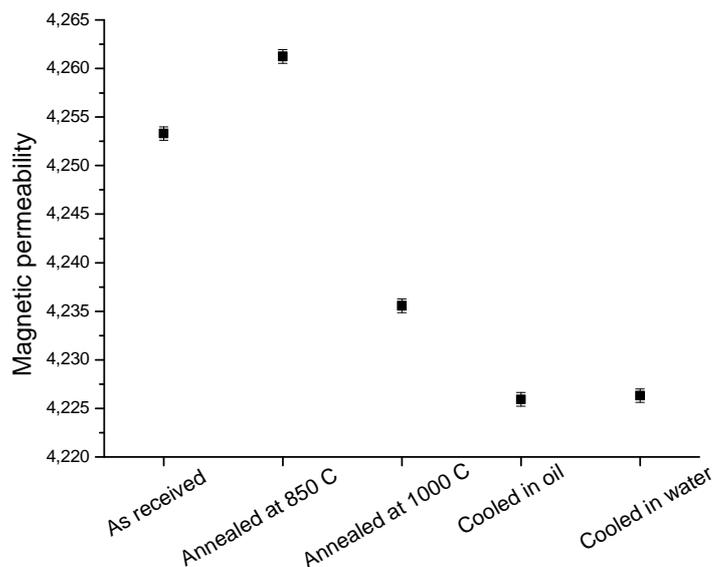


Figure 2. Variation of magnetic permeability measurements in the sample as received and in the samples as a function of the type of heat treatment applied, for the voltage of 5 V in the inductor coil.

The as received sample when annealing at a temperature of 850 $^{o}$C, which is at the intercritical temperature, leads to an increase in the amount of ferrite phase, which is ferromagnetic and increases the magnetic permeability. However, when annealing at 1000 $^{o}$C, there is an increase in the amount of pearlite in the steel, due to the time it was kept at elevated temperature. This constituent is formed by two ferromagnetic phases, ferrite and cementite in the form of lamellar structure. This configuration makes difficult the movement of the magnetic domains walls and gives the pearlite a paramagnetic behavior. Thus, it reduces the magnetic permeability of the material (Silva 2016a).

Cooling with oil and water from the temperature of 1000 $^{o}$C leads to the formation of martensite in 4340 steels. These steels have high hardenability due to the presence of alloying elements and, therefore, it is easier to obtain martensite. Thus, steel with high hardenability such as SAE 4340 is able to form martensite in thicker sections with low cooling rates. Martensite causes distortion of the crystal lattice and formation of thin strips that anchor the movement of magnetic domain walls and reduce permeability. The finer microstructure of martensite leads to a greater reduction in magnetic permeability values. The results show that permeability measurements were able to differentiate ferrite plus pearlite and martensite microstructures. Similar results were obtained by studying the variation of sonic velocity measurements and by Barkhausen magnetic noise analysis (El Rayes *et al.,* 2014, Gür and Çam 2007).

The results obtained from the hardness test in figure 3 shows that, as the microstructure become thinner, the greater is the difficulty in moving the magnetic domains walls and smaller are the permeability values. The hardness test is an already consolidated one and serves to help in the validation of the experimental bench in the magnetic permeability test. The increase in hardness causes a decrease in magnetic permeability and this correlation can be seen in Figure 3. By analyzing Figure 3, it is possible to verify that the sample that was subjected to quenching by cooling in water had the highest hardness value (63 HRC) and the lowest magnetic permeability value (4.226). Going to the other end of the same Figure, it is observed that the sample submitted to the annealing treatment at 850 ℃ had the lowest hardness values (20 HRC) and the highest magnetic permeability values (4.261). However, the permeability measurements obtained for the hardness of martensite were not able to differentiate between quenching in oil and in water.
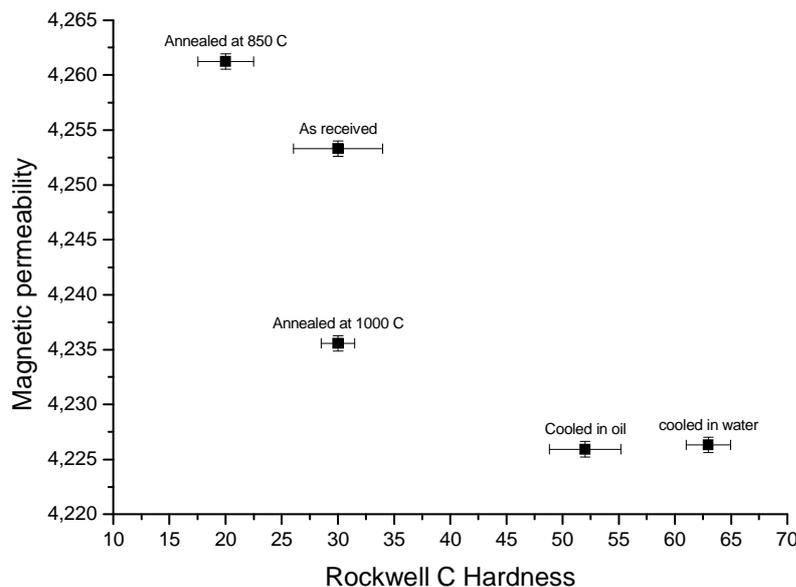


Figure 3. Variation of magnetic permeability measurements as a function of Rockwell C hardness measurements, for samples as received and submitted to the applied heat treatment.

Figure 4 shows the variation in magnetic permeability as a function of rotation angle for samples as received, annealed at 850 $^{o}$C and cooled in oil. Note that the three maintained the same behavior. This indicates the existence of a magnetic anisotropy in the material as received, due to the manufacturing process and that the imposition of the treatments performed did not modify this behavior.

The magnetic properties of electrical steels such as the core loss and magnetic induction depend on the microstructure and texture, which are produced through thermo-mechanical processing, involving slab reheating, hot rolling, cold rolling and final recrystallization annealing (Chen et al., 2014; Quin et al., 2015; Sonboli et al., 2015). These processes can also generate noticeable magnetic anisotropy in the material because the magnetic behavior of the steel strongly depends on its stress– strain state (Chwastek et al., 2013; De Albuquerque et al. 2010; Nunes et al., 2013) When testing polycrystalline ferromagnetic materials, it is often found that properties depend on the direction along

winch they were measured and that there are certain macroscopic orientations in which the material is easier to magnetize (magnetic easy axis) (Chen et al., 2014; Qui et al., 2015; Silva et al., 2016b). The three conditions in Figure 4 indicate a maximum magnetic permeability value for the 180 degree angle, that is, there is an easy magnetization direction towards the 180 degree angle. Silva et.al. (2016b) observed similar results when studying anisotropy in SAE steels 1040, due to the manufacturing process.
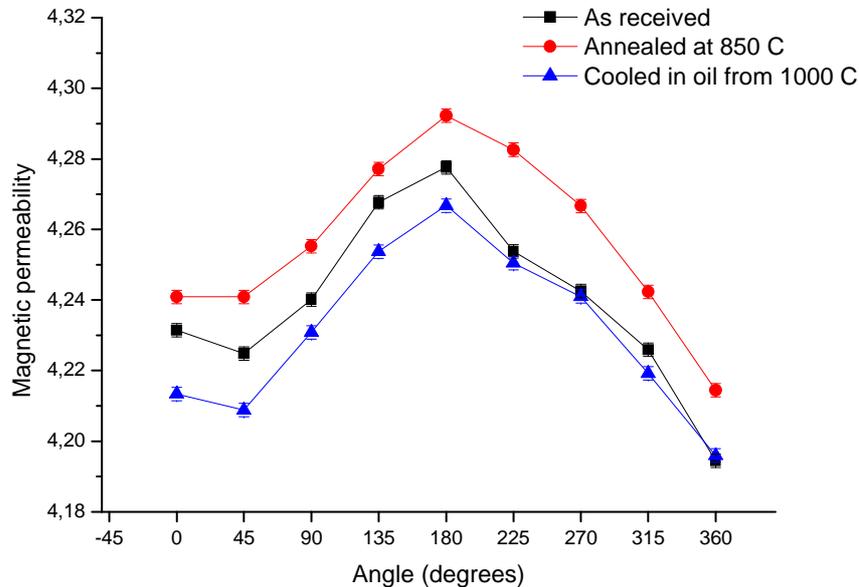


Figure 4. Permeability variation of each sample with its respective heat treatment, after they are rotated from 45º to 45º until complete rotation – 360º.

## 4. CONCLUSIONS

The present work studied the detection of heat treatment in samples of a SAE 4340 steel through measurements of magnetic permeability determined in the region of reversibility movement of the magnetic domains walls, reaching the following conclusions:

i.  The electromagnetic test was able to differentiate the heat treatments used in a SAE 4340 steel, being sensitive both to the variation of the ferromagnetic ferrite phase and the presence of the pearlite lamellar structure, which has paramagnetic characteristics due to its structure that anchor the movement of the magnetic domains walls. Furthermore, it was able to detect the presence of the martensite structure in samples quenched in oil and water.
ii.  The permeability measures had a good correlation with the hardness ones, showing to be able to be correlated with this. However, it was not able to differentiate the condition quenched in oil and water, which showed differences in hardness measurements.
iii.  The electromagnetic test was able to observe the existence of a magnetic anisotropy in the as received material, due to the manufacturing process and the imposition of the treatments performed did not modify this behavior.

## 5. ACKNOWLEDGEMENTS

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