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Magnetic Barkhausen Noise and Magneto Acoustic Emission in Stainless Steel Plates

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Abstract

When a slowly variable magnetic field (~ Hz) is applied through a yoke on a ferromagnetic material, discontinuous changes on the magnetic flow density are produced. This phenomenon, called Magnetic Barkhausen Noise (MBN), obeys the movement of magnetic domain walls and its frequency range is about [10-100] kHz. It involves sudden magnetization changes and localized variations of mechanical stresses which originate elastic waves known as Magneto Acoustic Emission (MAE) on the frequency range of 20 kHz up to 1 MHz. Both, MBN and MAE depend on the material microstructural characteristics and they may be considered as non-destructive evaluation techniques. This work is based on MBN and MAE tests carried out on 5 groups of different stainless steel specimens (AISI 409, AISI 430, AISI 439, AISI 441A and AISI 444), for two applied magnetic fields, parallel and perpendicular to the rolling direction.

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Key words: Magnetic Barkhausen Noise; Magnetic Acoustic Emission; stainless steel; material characterization.

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1. Introduction

In this paper, stainless steels from AISI 400 Series are studied. They are ferritic and have higher Cr concentration and lower C than martensitic ones (Carbó, 2008; Cardarelli, 2008). Their crystalline structure is BCC and they are ferromagnetic. Their high tolerance to corrosion is the fundamental characteristic to use this type of steels. They have at least 10.5 % Cr and other elements as Silicon (Si), Manganese (Mn) and Sulfur (S).

Ferromagnetic materials, submitted to a variable magnetic field, respond with the movement of their magnetic domain walls. In this situation small jumps can be seen in their hysteresis loop when the magnetic induction grows up. This phenomenon is known as Magnetic Barkhausen Noise (MBN). Additionally, magnetic domain wall movements produce variations in the stress field inside the material which gives rise to low amplitude and high frequency elastic waves known as Magneto Acoustic Emission (MAE). MBN and MAE depend on the micro structural characteristics of the material under study and they are part of the no destructive test techniques (Martinez Ortiz et al., 2010; Jiles, 1995; Freddy et al., 2007; Torres et al., 2009). The experimental evidence of the MBN was discovered by Henriech Barkhausen in 1919. From that date multiple studies were made related the influence of micro structure on the RMB, finding as an example that the amplitude of MBN increase with the grain size reduction (Torres et al., 2009). Some papers relate the MBN with the hardness and mechanical working (Freddy et al., 2007; Sullivan et al., 2004; Sullivan et al., 2004). The depth of the magnetic influence produced by an excitation frequency of 10 Hz is of the order of 10 mm. MBN is a superficial and sub superficial phenomenon because only information of near a maximum depth of 0.1 mm can be collected; on the other hand, MAE is produced in all the region affected by the magnetic field, so information about near 10 mm depth can be collected (Neyra Astudillo et al., 2012).

In this paper the characteristics of ferritic stainless steels from AISI 400 series are studied: 409, 430, 439, 441A and 444, produced by ArcelorMital Inox from Brazil (Carbó, 2008).

Preliminary studies that shall be included in a Doctoral Thesis are presented here.

2. Experimental Procedure

Most important characteristics of the stainless steel plates are described in next paragraphs.

2.1. Materials

All the studied samples were obtained from plates (original dimensions of 300.0 mm x 210.4 mm x 0.5 mm) of ferritic stainless steel of types AISI 409, AISI 430, AISI 439, AISI 441A and AISI 444, whose chemical compositions are presented in Table 1. The samples were submitted to a variable magnetic field, produced by means of a solenoid. Due to the small plate thickness, the samples had to be introduced inside the solenoid in order to have the MAE phenomenon clearly detected. Although the magnetic field was applied to the entire sample piece to give rise to notable MAE, the collected MBN was produced only below the area covered by the sensor coil. So, from each steel plate, different test sample pieces were cut according to the solenoid dimensions. On the left hand side of figure 1, one original steel plate can be seen (figure 1.a). On the right, cut samples to be tested can be seen on figure 1.b). The black arrow indicates the rolling direction. Samples used in this work (identified as “d” and “c”) were cut in the rolling direction (0^o) and perpendicular to it (90^o).

Table 1. Chemical composition, % (Weight).

% (Weight)	409	430	439	441A	444
C ≤	0.08	0.12	0.07	0.03	0.025
Cr	10.5/11.75	16/18	17/19	17.5/18.5	17.5/19.5
Ti ≥	6 x C		0.20 + 4 (C+N)		
Nb≥				3 x C + 0.30	
Ti + Nb ≥					0.20 + 4 (C+N)
Mo					1.75/2.50

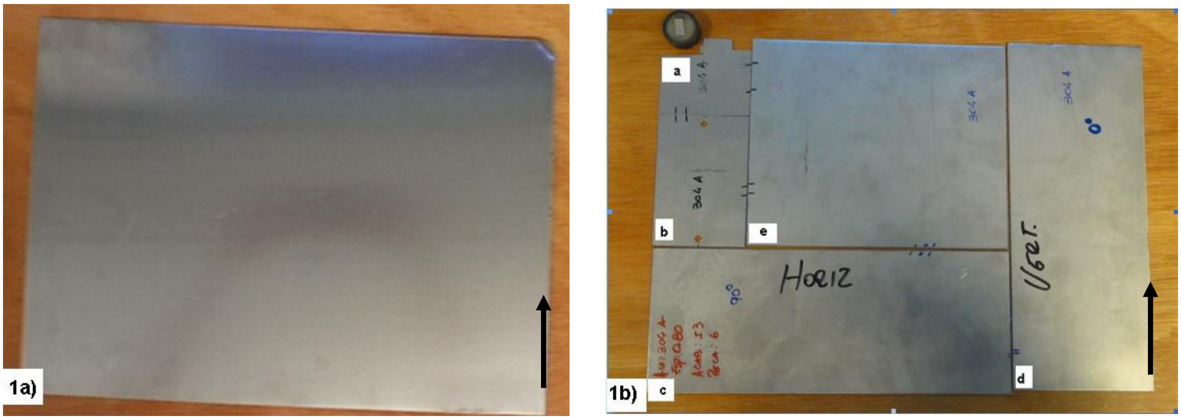

Fig. 1. a) Photograph of one of the stainless steel plates; b) diagram of the cuts made on the plates.

2.2. Micro Structural characterization

All the stainless steels plates studied are identified with AISI nomenclature, so here, for simplicity, only their numerical references are used. Figure 2 shows pictures of the plates micro structures, the black arrows indicating the rolling direction (Castillo Guerra, 2012).

2.3. Micro Hardness

The Vickers micro hardness of all the stainless steel plates was tested with a charge of 0.1 kg. The values are showed at table 2.

Table 2. Vickers micro hardness

Steel	**$HV_{0.1}$**
409	144
430	173
439	173
444	205
441A	208

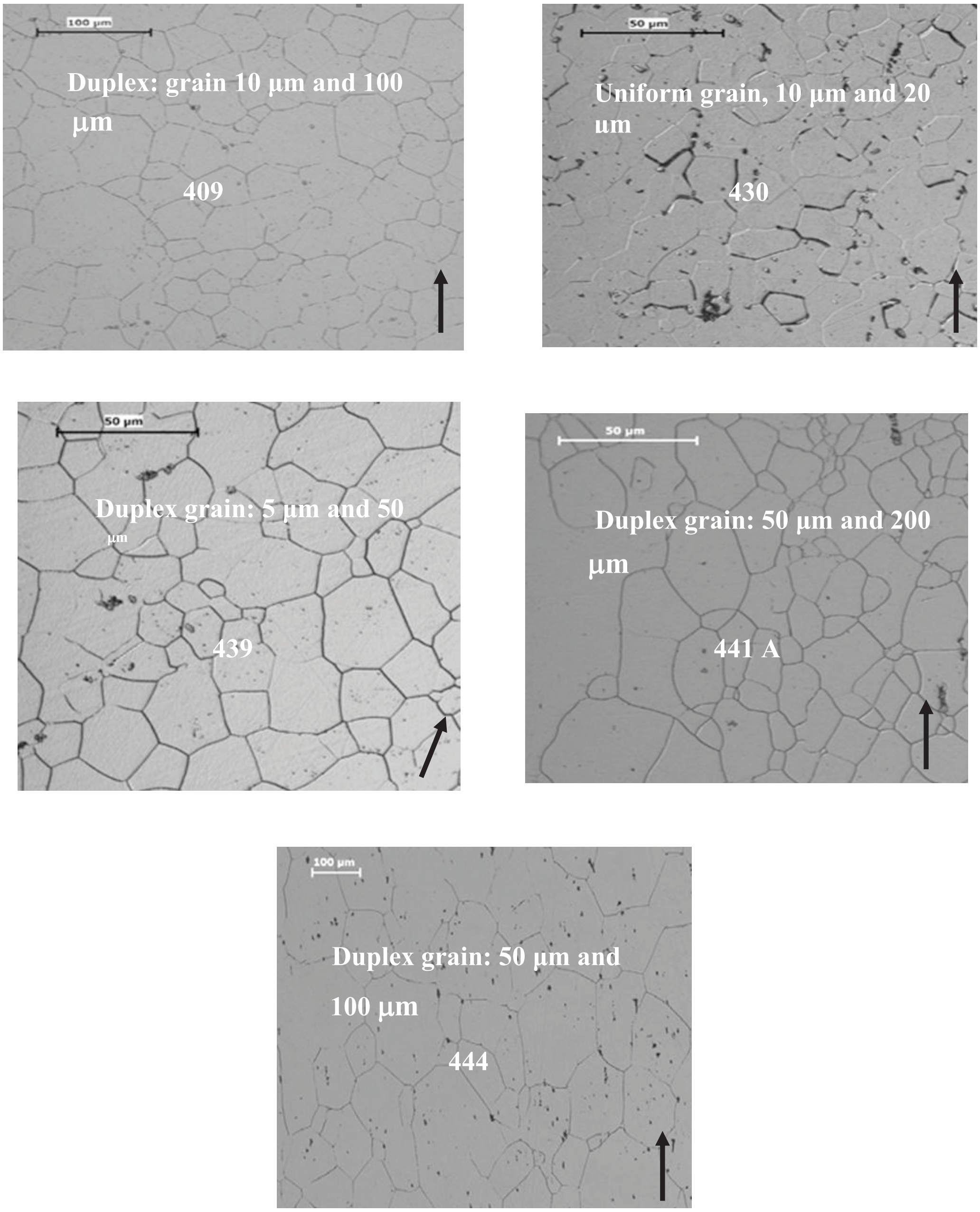

Fig. 2. Ferritic structure of the stainless steels. The black arrow indicates the rolling direction. In each picture the steel identifications and grain sizes are indicated.

2.4. Magnetic Barkhausen Noise and Magneto Acoustic Emission studies

The magnetic field was produced by a variable current on a solenoid coil. Test sample pieces (see "c" and "d" in figure 1.b) were introduced inside the solenoid. To capture the MAE, a two channels Acoustic Emission (AE) system was used. One channel was used with a resonant sensor (150 kHz, PAC R151-AST S/N DN32) and a wide band sensor (WD 100-800 kHz, PAC WD S/N AE65), each one with a 40 dB pre amplifier with low noise level (< 7 μV). An appropriate couplant was used. The MBN sensor coil and both AE sensors were fixed to the test piece using insulating tape. Experimental set up can be seen in the photograph of figures 3 and 4. A 10 Hz sinusoidal wave produced by a function generator LeCroy ARB Studio 1102 with amplitude of 1 V, amplified through a power amplifier specially designed, excited the solenoid coil. The maximum current intensity on the solenoid was 0.15 A, measured on a series 10 Ohm resistor. The 1500 turns solenoid were 18 cm long with a 9.5 cm diameter. The MBN sensor used a specially designed amplifier with a band pass [1-500] kHz with low noise level. MBN and MAE measurements were made on 10 test pieces, cut one at 0^o and other at 90^o, from the 5 different stainless steels. All the signals were registered on a digital LeCroy oscilloscope with the following details: channel 1, MBN signal; channel 2, wide band AE sensor; channel 3, resonant AE sensor; channel 4, ΔV on the 10 Ohm resistor. In previous test, the null interference between the AE sensors and the magnetic field was checked.

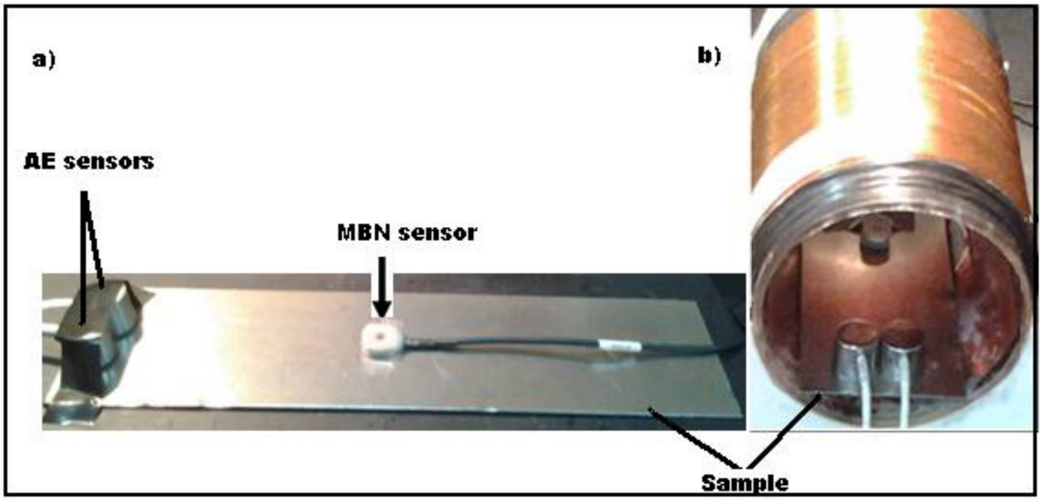

Fig. 3. a) Photograph of the test piece with 2 AE and MBN sensors. b) Photograph of the test piece inside the solenoid with the 3 sensors coupled.

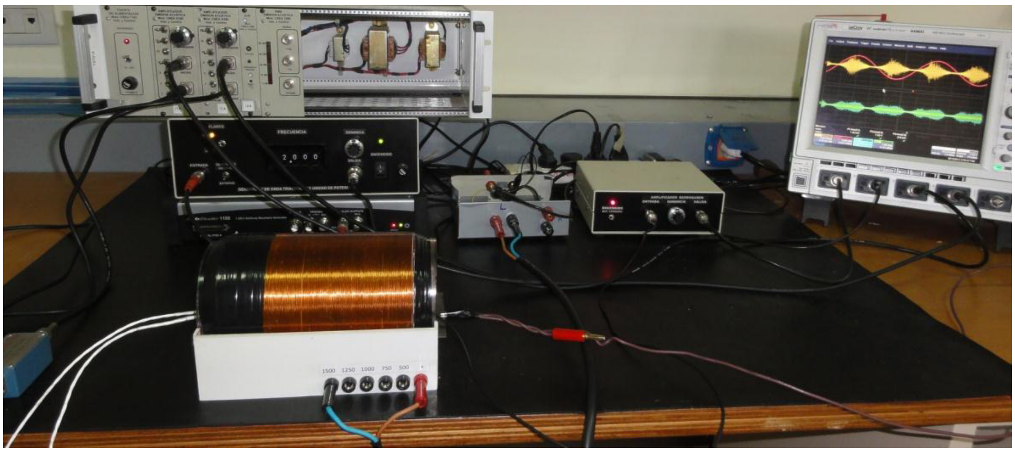

Fig. 4. Photograph of the whole MBN and MAE experimental system.

3. Results and discussion

From each test, 4 files were recorded: two for MAE (resonant end wide band sensors); one for the excitation current, and the other for MBN, thus for 0° and 90° (for each steel), giving 8 recorded files for each material. All signals were digitalized with a frequency of 2.5 MSamples/s. MBN and MAE signals were processed with the help of Matlab software, their envelopes and RMS functions having been calculated.

In a first step, all the signals from the resonant and wide band AE sensor were compared. Since their behavior was similar, only the signals from the resonant AE sensor (more sensitive) are here analyzed. As an example, in figure 5 MBN signals from 0° and 90°, for 441A (highest hardness) and 409 (lowest hardness) steels are showed vs. sample number (0.4 μs between two consecutive counts). Differences in form and amplitude are notable, both related with rolling direction and hardness. The hardest material (441A) has the highest RMB values.

The same representation was used in figure 6 with MAE signals. Similarities were found, but in this case, the higher amplitude signals belong to 409 steel (lowest hardness). So MBN and MAE signals have opposite behavior related with hardness, but both are different related with the magnetic applied direction and hardness.

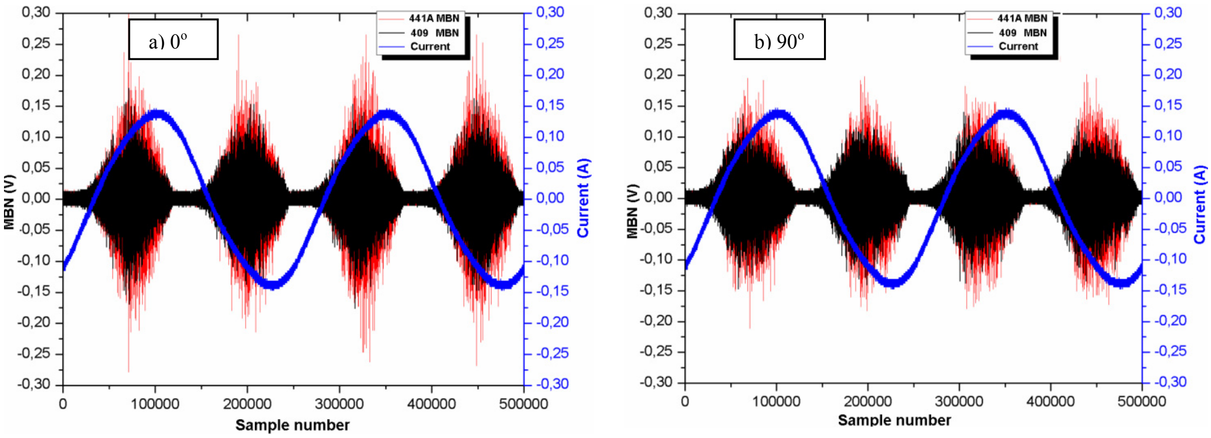

Fig. 5. MBN superimposed signals for 441A and 409 steels. a) for 0° and b) for 90°.

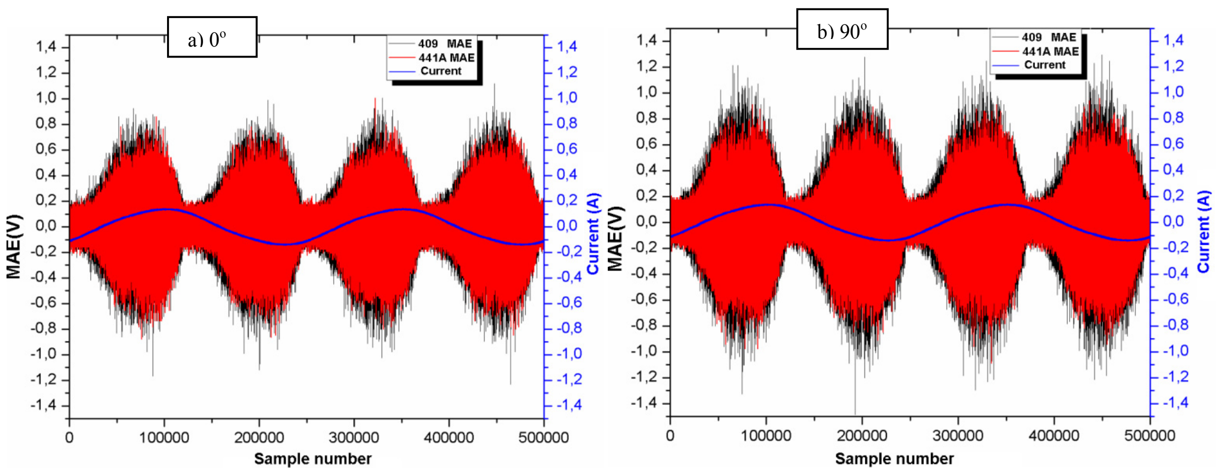

Fig. 6. MAE superimposed signals for 441A and 409 steels. a) for 0° and b) for 90°.

Considering figure 2, for 430, 439 and 444 micrographics, the precipitates show a preferential orientation in the rolling direction. For 441A (figure 2) a small grain stretching in rolling direction can be viewed. These last conditions may contribute to explain the differences found between MBN and MAE signals at 0° and 90°.

In figure 7 the envelopes of MBN signals are showed for all the steels; on the left side for 0° and on the right side for 90°. It is easy to see notable differences for different magnetic applied field directions and different steels. For each material, the highest amplitudes can be seen for 0° and differences on the envelope shapes are notable for the different steels. With the same procedure, the envelopes of MAE signals can be analyzed in figure 8. For each material, relative higher amplitudes can be seen for 0° and differences on the envelope shapes are notable for the different steels.

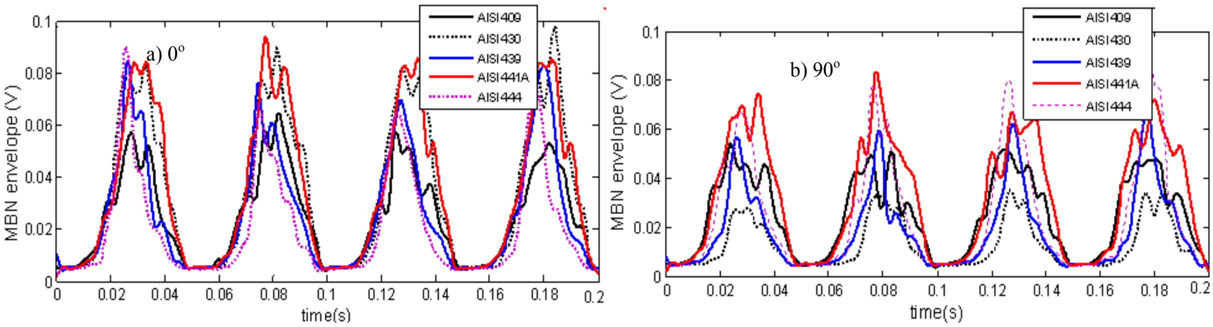

Fig. 7. MBN envelopes for all steels, a) for 0° and b) for 90°.

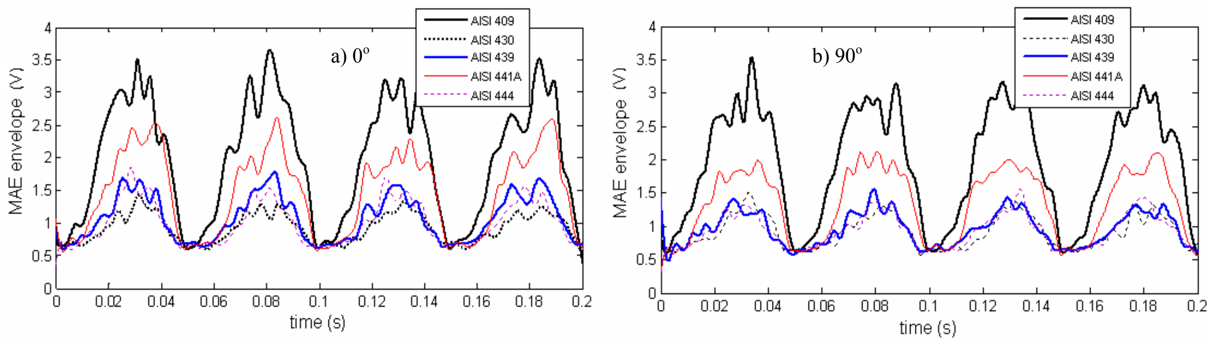

Fig. 8. MAE envelopes for all steels, a) for 0° and b) for 90°.

On the other hand, figures 7 and 8 are showing differences related with grain size (different for each steel), but, as some steels have duplex size, the correlation is not easy to explain.

Observing the MBN envelopes for rolling direction (0°, figure 7. a), the corresponding curve for 441A presents the highest amplitude, while lowest one concerns the 409 steel curve. The grain size for 409 steel is duplex, 10 µm and 100 µm, and also for 441A, 50 µm and 200 µm. According to Torres at al. (2009), in zones with coarse grain and low dislocation density there is a low number of domain walls moving. Also the increase in the distance between dislocations and grain boundary reduces the number of emissions but increase their amplitudes. Additionally, with the increment of grain size, the envelope diminishes (Freddy et al., 2007; Torres at al., 2009). This behavior is not seen with the MBN envelopes (see figure 7), probably due to the duplex type of grain size with two grain sizes simultaneous. A deeper analysis, not included here, is needed. As for example, the Fourier analysis of MBN and the wide band MAE signals may be studied, the different forms of the envelopes should be explained including the relative peaks in each envelope.

Figure 9 shows the calculated RMS values of MBN signals for each steel, taken acount their chemical composition (mainly Cr content), in conjunction with the Vickers micro hardness for 0^o and 90^o. The same procedure was used in figure 10 to present the calculated RMS values of MAE. From table 1 and 2, it can be seen that the micro hardness grows with Cr content and some alloy components. Steel 409 with only 11 % Cr content has the lowest micro hardness. 430 and 439 steels have equal micro hardness, near the same Cr content, but 439 steel has a small Ti %, which dissolves principally in the ferrite and stabilizes it reducing its free energy. 444 steel has excellent corrosion resistance thanks to the presence of near 2 % Mo in the alloy. 441A steel is similar to 439, it has a better yield strength at high temperatures due to the higher Nb quantity and it is harder (Carbó, 2008; Cardarelli 2008; Jiles 1995; Anteri et al., 2012) These notes justify the different micro hardness of these steels and the order selected to represent them in figures 9 and 10.

In figure 9 the tendencies of RMS values of MBN are different for 0^0 and 90^0. In the case of figure 10 for MAE and micro hardness, the same tendency for 0^0 and 90^0 can be seen.

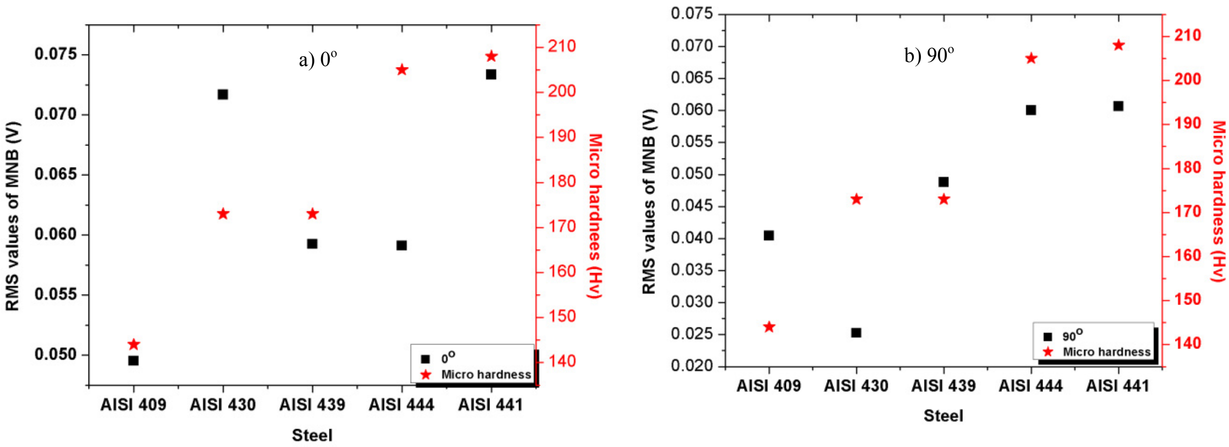

Fig. 9. RMS values of MBN and Vickers micro hardness vs. different stainless steels.

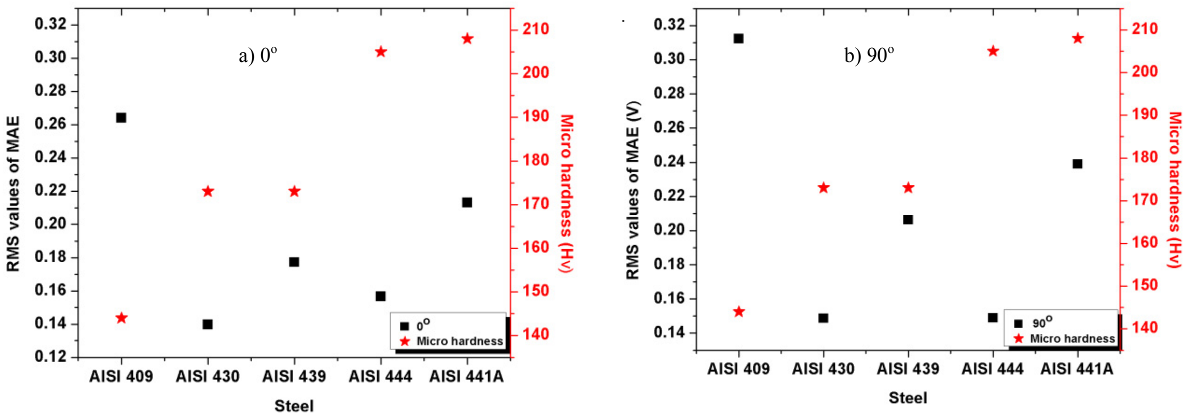

Fig. 10. RMS values of MAE and Vickers micro hardness vs. different stainless steels .

4. Conclusions

Preliminary results of MBN and MAE tests carried out on specimens cut at rolling and transversal directions from 5 different ferritic stainless steel plates (AISI series) were studied. They are part of a Doctoral Thesis.

Metallographic characterizations of each material were made and their micro hardness measured. At present, only the RMS and envelopes curves of MBN and MAE signals were analyzed.

Notable differences at envelopes curves were found for both MBN and MAE, but to justify these behaviors a deeper analysis is needed, considering the frequency content of the signals. The reasons for the relative peaks of the envelopes, for both MBN and MAE signals and their causes, have still to be clarified.

Additionally, texture and residual stresses studies are also still to be made. Strain tests with uniaxial stress shall be performed for specimens cut at rolling and transversal directions from these different ferritic stainless steel plates.

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