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HARMONIC ANALYSIS OF ELECTROMAGNETIC WAVES FOR DETECTING EMBRITTLEMENT MICROSTRUCTURES IN A DUPLEX STAINLESS STEEL

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Abstract. *The magnetic properties depend on several characteristics of the materials, such as chemical composition, microstructure, hardness, stress states, deformations and heat treatments. Electromagnetic waves traveling through ferromagnetic materials bring information about the microstructures present. These interfere with the amplitude of the harmonics of the applied wave. In the present work, the amplitude of the emitting wave harmonics is studied to accompany embrittlement phases in duplex stainless steels SAF 2205. It at a temperature above 600 °C is characterized by having its mechanical properties and corrosion resistance compromised, due to the formation of a phase called sigma. An electromagnetic test composed of an emitting coil and a Hall effect sensor, with samples positioned between them, was applied. Emitting waves of 5 Hz, 10 Hz, 15 Hz and amplitudes from 0.25 V to 9 V were used and the first harmonic were analyzed. The measurements obtained by the electromagnetic test were correlated with the hardening of the material and its ability to absorb energy by impact. The amplitude values of the harmonics show that they are able to detect the presence of the precipitates and that their presence reduces the amplitudes due to the blocking of the movement of the domain walls.*

Keywords: *embrittlement phases, electromagnetic test, harmonic analysis, Hall effect sensor, duplex stainless steel.*

1. INTRODUCTION

When a magnetic field is applied to a ferromagnetic material, the resulting magnetic induction has a distorted shape due to magnetic hysteresis and the non-linearity of the material's permeability, that is, an applied sine wave induces a non-sinusoidal one. This distorted waveform of magnetic induction contains components in the harmonic frequencies of the applied magnetic field (İSPİRLİ and YILMAZ, 2018, Xia at al., 2016).

Harmonic analysis has been applied in investigation on characteristics of tracking failure in epoxy resin (SPİRLİ and YILMAZ, 2018), detection of corrosion degradation using electrochemical noise (Xia at al., 2016), nondestructive evaluation of aged steel by harmonic analysis of induced voltage (Ryu et al., 2001), measurement techniques for material state determination in metals (Matlack et al., 2015) and Monitoring of embrittled paramagnetic microstructure using harmonic analysis of induced stress in stainless steels (Silva et al., 2018) .

Magnetic properties depend on several characteristics of materials, such as chemical composition, microstructure, hardness, stress states, deformations and thermal treatments (Lo et al., 2011, Miesowicz et al., 2016, Ducharne et al., 2017, Silva et al., al., 2016a, Silva et al., 2016b, Silva et al. 2016c, Camerini et al., 2015). The SAF 2205 steel, when subjected to treatment above 600 °C, has the formation of a paramagnetic phase called sigma. The presence of this changes the magnetic permeability of the material. An amount of 4% of this phase is able of compromising the toughness and corrosion resistance of this material. Non-destructive tests have been developed to monitor the sigma phase, in order to determine the best time for intervention (Tavares et al 2010, Silva et al., 2016).

In the present work, an electromagnetic test composed of an emitting coil and a Hall effect sensor, with samples positioned between them, was applied, in order to detect the sigma phase presence. Emitting waves of 5 Hz, 10 Hz, 15 Hz and amplitudes from 0.25 V to 9 V were used and the first harmonic amplitude were analyzed. The measurements obtained by the electromagnetic test were correlated with the material hardeninge and its ability to absorb energy by impact. This work gives a contribution to system for detecting the sigma phase by changing the receive coin by a Hall effect sensor in order to simplify the test.

2. METODOLOGY

The test equipment consists of two modules, one for emission and one for acquisition. The scheme of the new experimental configuration is detailed in Figure 1. The emission module is composed of a Minipa function generator model MFG 4205B and the emitter coil. The function generator transmits sinusoidal waves to the emitting coil. The coil is positioned in the center of one of the faces of the sample , having the function of introducing a magnetic flux density into the material.

The acquisition module consists of a Hall effect sensor, an acquisition board and a computer. The sensor is positioned in the center of the other face of the sample, in order to detect the field resulting from the interaction between the emitting wave and the material. The acquisition board connects to the sensor and computer via USB cables. The computer performs automatic data acquisition using the Permeability program developed by the group. The coil used is 19.5 mm long and has 6000 turns of No. 38 enameled copper wire wrapped around an AISI 4140 steel core.

The chosen sensor is Hall effect, linear, model SS495A, from Allegro Microsystems, with a sensitivity of 3.125 mVolts/Gauss and a supply voltage between 0 and 10 V, supplied with a continuous voltage of 5 V.

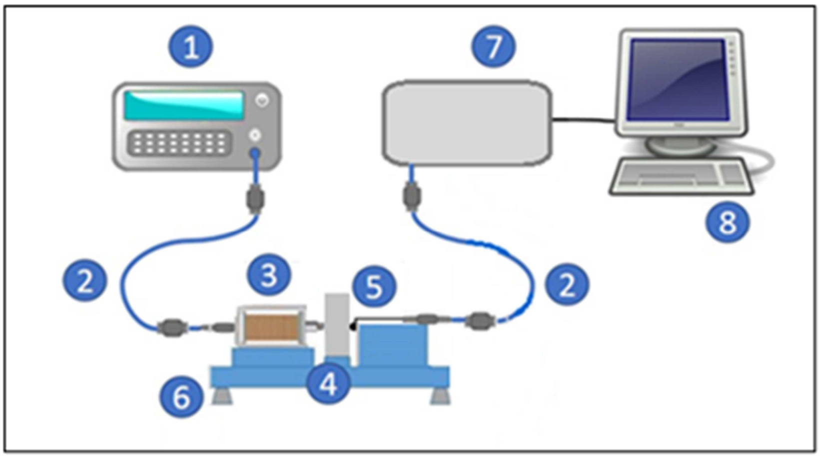

Figure 1. Experimental setup: (1) signal generator, (2) shielded cables, (3) transmitter coil, (4) sample, (5) Hall effect sensor, (6) Faraday cage test bench, (7) acquisition board and (8) computer.

To determine the characteristics of the optimal emitting wave for testing, two samples with a thickness of 8 mm and a diameter of 24 mm were used. One in the as-received condition, which does not present precipitates, and the other treated at a temperature of 850 °C, aged at 15 min. This treatment is already sufficient to form 4% sigma phase (Tavares et al. 2010, Silva 2016a). The objective was to determine the best wave to produce a measurement amplitude between the two conditions, in order to have the sensitivity to follow the formation of the σ phase.

Sine wave signals were applied, with frequencies of 5, 10 and 15 Hz and amplitudes of 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 3, 5, 7 and 9 V, on the emitter coil. The acquisition of 1000 points every 1 s was performed through the Hall effect sensor positioned on the opposite side of the sample in relation to the emitting coil. Fifty signals of each frequency and amplitude array were captured for each sample, with the objective of analyzing the region that produces the greatest difference between the condition with and without treatment.

The parameter used for wave analysis was the RMS. This parameter was chosen due to its simplicity and successive use in the literature to interpret the magnetic Barkhausen noise. The RMS value is calculated according to Equation (1).

$$x_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} \quad (1)$$

Where:

N: element number in the measurement sequence;

$x_{i:}$: RMS amplitudes.

The RMS of the signals were obtained with a confidence interval of 95%, after applying the FFT (Fast Fourier Transform) of the same.

Electromagnetic tests were correlated with Rockwell C hardness measurements and energy absorbed by Charpy impact test. Five hardness measurements were taken on each sample and five normal Charpy samples were made in each condition. Measurement results were obtained with a 95% confidence interval.

3. RESULTS AND DISCUSSIONS

Electromagnetic tests have been developed to monitor the formation of embrittlement microstructures produced by thermal cycles as in welding processes. The interaction between a wave transmitted to the material and its microstructure causes distortions in the wave both in the form of noise, which is called Bakhausen magnetic, and distortions in the harmonics of the main wave. The latter is approached from the application of emitting waves at frequencies of 5Hz, 10 Hz and 15 Hz in Figure 2. These frequencies were chosen because they are applied in tests to monitor microstructures harmful to the toughness properties of materials through analysis of magnet Barkhausen noise (Kaleli et al., 2020, Tavares et al., 2019, Yamazaki et al., 2019, Ghanei et al., 2014, Normando et al., 2010).

Figure 2 shows the variation in magnetic flux density as a function of the amplitude of the emitting wave, for frequencies of 5 Hz, 10 Hz and 15 Hz applied in the as-received and treated condition at 850 ^{o}C for 15 min. It can be seen from Figure 2 that a reduction for the magnetic flux density measurements for the treated sample, for the studied frequencies. This reduction is associated with the paramagnetism of the formed sigma phase and the blocking of the movement of the walls of the magnetic domains with the formation of precipitates (Silva et al., 2016a). Duplex stainless steel is formed by two phases, one ferrite (ferromagnetic) and the other austenite (paramagnetic), the ferrite decomposes forming the sigma paramagnetic phase and a secondary austenite, thus reducing the ferromagnetism of the material (Tavares et al. 2010, Silva 2016a).

It is also observed from Figure 2, that the application of the three frequencies, indicates an increase in the values of magnetic flux density and the difference between the conditions with and without treatment. As the amplitude of the emitting wave increases, there is an increase in the magnetic flux and detection of a greater amount of paramagnetic phase and an increase in the difference between the two conditions studied. This indicates that the drop observed for the amplitudes of 2 V and 3 V of the emitting wave is possibly due to the growth in the detection of paramagnetism, which now surpasses that of blocking the movement of the walls of the magnetic domains. The as received condition is formed by a ferromagnetic phase ferrite and a paramagnetic one austenite, while the treated one differs from it by the presence of the paramagnetic sigma phase. Amplitudes above 2 V lead to the influence of the austenite phase that is presented in both conditions and dislocates both. However further work are needed to make it clear in the future.

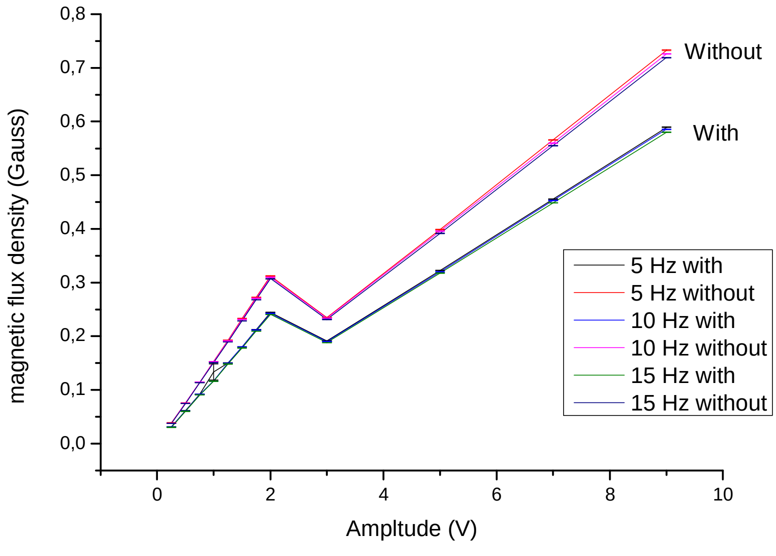

Figure 2. Variation of magnetic flux density as a function of emitting wave amplitude, for samples with and without precipitate and frequencies of 5 Hz, 10 Hz and 15 Hz.

In order to determine the best working region among the studied waves, the percentage variations between the conditions as received and treated were determined. Figure 3 shows the variation in percentage as a function of the amplitude of the emitting wave for the studied frequencies. Note that the highest percentages were in the region of amplitudes between 1 V and 2 V, where the differences were above 27.5%. This region presents larger measurement amplitudes for sigma phase detection. Figure 3 shows that the application of waves with amplitudes from 3V to 9V presented values below 24% and little variation in growth between them.

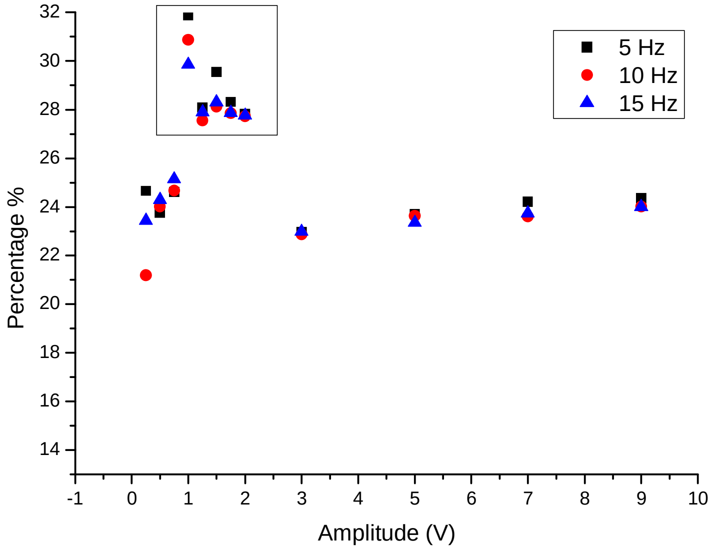

Figure 3. Variation in the percentage of amplitude of measurements between the condition with and without the sigma phase, for application of emitting waves at frequencies of 5 Hz, 10 Hz and 15 Hz.

The conditions with and without the presence of the sigma phase present hardness and energy absorbed by impact as shown in Figure 4. It can be seen from Figure 4 that the amount of 4% of sigma phase formed causes a small increase in hardness of 20.14 + /- 1.26 to 21.6 +/- 1.44. However, the absorbed energy measures drop from 76.67 J +/- 9.73 J to 16.5 J +/- 6.69 J. This difference is due to the sigma phase has hardness around 1000 HV and compromises the tenacity of the material. Magnetic flux density measurements varied about 32 % for sine waves with an amplitude of 1 V and proved to be effective in detecting even small amounts of sigma phase.

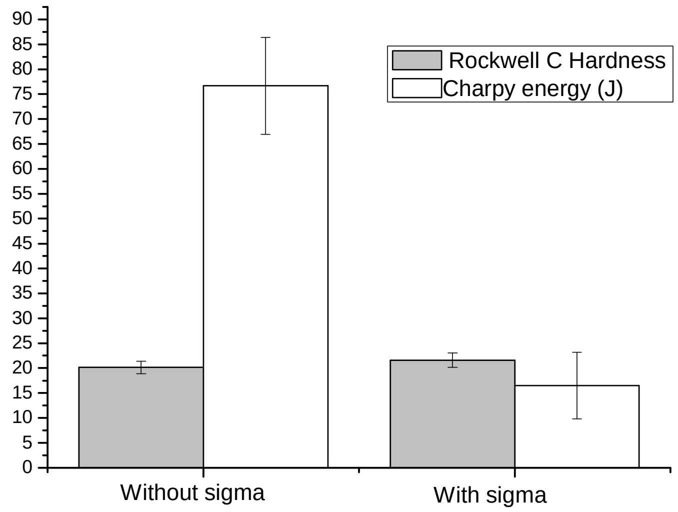

Figure 4. Rockwell C hardness measurements and energy absorbed by Charpy impact for conditions with and without the presence of sigma phase.

4. CONCLUSIONS

The present work performed an analysis of electromagnetic wave harmonics for the analysis of embrittlement microstructures in a duplex stainless steel, using waves with frequencies of 5 Hz, 10 Hz and 15 Hz and amplitudes from 0,25 V to 9 V, reaching the following conclusions:

- The study of harmonics was able to detect the presence of sigma phase of the studied duplex stainless steel. The magnetic flux density measurements reduced with the presence of the sigma phase formed due to paramagnetism and blocking of the magnetic domains movements due to the presence of formed precipitates.
- Waves with frequencies of 5 Hz, 10 Hz and 15 Hz presented similar behavior for conditions with and without the presence of the sigma phase.
- Waves with amplitudes in the range of 1 V to 2 V show to have the best measurement amplitudes for monitoring the formation of the sigma phase above 27%, while in the range of 3 V to 9 V they presented values below 24%.
- Charpy energy measurements show that an amount of 4% sigma phase is already sufficient to reduce the energy absorbed by impact by 78%, despite a 7% increase in hardness. However, magnetic flux density measurements have a measurement amplitude around 32 % for waves with amplitudes of 1V in the studied frequency range.

5. ACKNOWLEDGEMENTS

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