Detection of the best working region in an electromagnetic test for sigma harmful constituent analysis

J. B. O. Silva[1], E. M. Silva[1], R. S. A. T. Lins[1], S. L.C. Alencar[1], S. É. N. Correia[1], J. P. Leite[2]

[1] Instituto Federal de Educação Ciência e Tecnologia da Paraíba, Av. Primeiro de Maio, 720 - Jaguaribe, João Pessoa - PB, 58015-435, Brazil.

[2] Universidade Federal da Paraíba, Jardim Universitário, s/n - Castelo Branco, João Pessoa - PB, 58051-900, Brazil. Email:Type the author addresses here

silvajbo@ifpb.edu.br , edgard@ifpb.edu.br, , rayssasatlins@gmail.com, suelen.carvalho@academico.ifpb.edu.br suzete@ifpb.edu.br, josinaldo@ct.ufpb.edu.br

Abstract. There are several equipments for non-destructive tests using Magnetic Barkhausen Noise (MBN) principle. This work proposed a new electromagnetic test configuration based on the MBN analysis, using an emitter coil and a Hall effect sensor, to detect the presence of the sigma phase in a Duplex Stainless Steel. Two samples of AID SAF 2205 were used. One in the as received condition, that is, without showing precipitates and one treated at 850 °C, aged for 15 min. Signals of electromagnetic sine waves were applied through an emitting coil, these passed through the material and a Hall sensor, positioned after the material, receives the waves resulting from the interaction. The electromagnetic waves resulting from the MBN effect were studied by subjecting the samples to magnetic fields with varying frequency and amplitude, in order to detect the presence of the sigma phase in the material. The test showed that it is possible to replace the receiver coil, in the traditional configuration by the Hall effect sensor. It was observed that the application of waves with frequencies from 5 Hz to 50 Hz can be used with amplitudes between 1 V and 2 V for detecting the sigma phase.

1. Introduction

Ferromagnetic materials have magnetic domains, which are regions with uniform magnetic orientation. When applying a variable magnetic field to the material, the walls of the domains move, generating displacements that tend to form larger domains, oriented according to the direction of the applied field. This movement is not continuous, but performed in leaps, depending on a series of micro and macro-structural factors [1-5]. It is possible to relate the magnetic jumps generated by the movements of the walls to the noise generate in the electromagnetic wave in the signal. These are known as Magnetic Barkhausen Noise (MBN), a magnetic phenomenon that has been considered as a useful parameter in several applications, such as non-destructive evaluation of residual stresses, deleterious phase detection, presence of precipitates, investigation of different grain sizes, identification of different stages of tensile deformation and monitoring of fatigue damage [5-10].

The MB

N is measured with the aid of an electromagnetic emitting and a receiving coil. The RMB parameters depend on the frequency and waveform of the excitation magnetic field. The frequencies used are in the range of 0.1 Hz to 1 kHz and the waveforms most used in the magnetic excitation of the material are sinusoidal and triangular [11-17].

Hall effect sensors are low cost and simple to use, which is why they are used in electrical systems in a wide most varied applications, ranging from sensing, tachometers, position meters, magnetic field, among others. As this sensor is very sensitive to the variation of the magnetic flux, its output signal is strengthened as the magnetic surface approaches. These sensors have been used in electromagnetic tests to detect microstructural variations in different materials [2-4].

Duplex Stainless Steels (DSS) have a different mechanical behavior from other stainless steels, due to their microstructure, which is formed by two phases (hence the name “duplex”) in similar proportions, austenite and ferrite [1-5]. This steel has excellent performance when subjected to severe conditions of pressure and corrosion, reaching a durability up to four times greater than other stainless steels [1-5].

The DSS have good resistance to fatigue, good toughness and resistance to impact, which makes their use possible in applications where the risk of equipment failure can lead to environmental damage, costs and even human losses. However, when these are subjected to thermal cycles above 550 °C, they suffer embrittlement, as a result of the formation of coarse precipitates on the contours of a phase called sigma (σ), which is rich in Chromium (Cr) and extremely hard, which compromises the corrosion resistance and toughness of the material, only 5% of which is needed for this to occur [1-5, 16,17].

This work studied the ability to replace the receiving coil with a Hall effect sensor, in an electromagnetic test based on the MBN analysis. The wave followed the material and a Hall effect sensor, positioned after the material, receives the wave resulting from the interaction. The sensor was the difference in the new configuration, as traditional methods use two coils, one emitter and the other receiver. The characteristics of the electromagnetic wave for generating the MBN were studied by applying waves with different frequencies and amplitudes. A duplex stainless steel was chosen for this study because it presents a change in permeability due to the formation of a phase called sigma. Small amounts of this are already enough to the embrittlement of the material and its detection served to qualify the test.

2. Materials and methods

To carry out this work, two samples of DSS SAF 2205 were used, machined in a circular shape, with a diameter of 24 mm and a thickness of 8 mm, one as received, that is, without aging, and other aged at a temperature of 850 °C for 15 min, in an induction furnace and cooled in water. This treatment is capable of generating 5% sigma phase in the material, enough to the embrittlement of the steel under study, affecting its microstructure and compromising its mechanical properties.

The equipment test consists of two modules, one for emission and one for acquisition. The scheme of the new experimental configuration is shown in Figure 1. The emission module is composed of a Minipa function generator model MFG 4205B and the emission coil. The function generator transmits waves of different formats to the emitting coil, with sinusoidal waves being used in this work. The coil is positioned in the center of the sample face, having the function of introducing a magnetic flux density in the material. The coil used is 19.5 mm long and has 6,000 turns of 38 AWG enameled copper wire wound on an AISI 1040 steel core.

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 sample face, 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 program developed by the group.

The chosen sensor is a linear Hall effect sensor, model SS495A, from Allegro Microsystems, with sensitivity of 3.125 mVolts/Gauss and voltage supply between 0 and 10 V, supplied with a continuous voltage of 5 V and this sensor saturates with 700 Gauss.

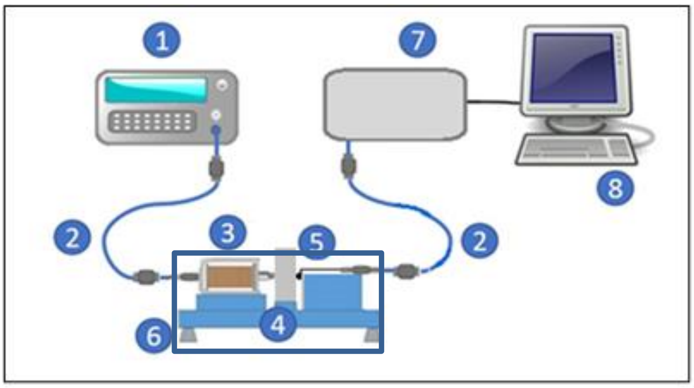

Figure 1 - Experimental setup: (1) signal generator, (2) shielded cables, (3) emitter coil, (4) sample, (5) Hall effect sensor, (6) test bench with Faraday cage, (7) acquisition board and (8) computer.

Sinusoidal wave signals were applied, with frequencies of 5 Hz, 10 Hz, 20 Hz and 50 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 was performed every 1 s, through the Hall effect sensor positioned on the opposite side of the sample in relation to the emitting coil, which detected the MBN.

Fifty signals of each frequency and amplitude arrangement were captured for each sample, with the objective of analyzing the region that produces the greatest difference in root mean square (RMS) of the signal between the condition with and without treatment. The parameter used for wave analysis was the root mean square of the wave signal. This parameter was chosen due to its simplicity and successive use in the literature to interpret the MBN. The RMS of the signals were obtained with a confidence interval of 95%, after applying the FFT (Fast Fourier Transform) of the same, with a high pass filter from 150 Hz.

3. Results and Discussions

Duplex stainless steel has good mechanical properties and corrosion resistance in the as received condition, in which it has only the presence of the constituents ferrire and austenite. However, when subjected to heating above 600 ºC, the formation of the sigma constituent occurs, which has hardness around 1000 HV and is rich in chromium, compromising the toughness and resistance to corrosion. Figure 2 shows the presence of the sigma constituent in the stainless steel SAF 2205 studied. This was obtained by attack with the 10% KOH reagent, which reveals preferentially sigma [1-5].

The present work showed the ability of a Hall effect sensor to replace the receiving coil and capture the Barkhausen magnetic noise in an electromagnetic test capable of detecting the presence of 5% of the sigma constituent. This section presents the conditions of amplitudes and frequencies of the emitting waves for carrying out the tests on DSS samples, with aL thickness of 8 mm [1-4].

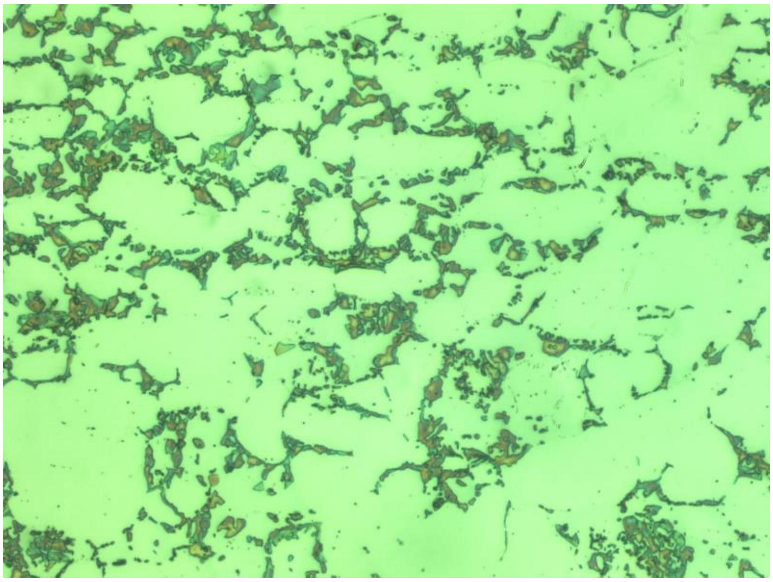

Figure 2– Optical microscopy of the steel heated to 850 ºC for 15 min. 200X magnification.

Figure 3 shows a sine wave with a frequency of 5 Hz and an amplitude of 5 V, emitted by the signal generator in the coil and captured by the Hall effect sensor, with sample without treatment.

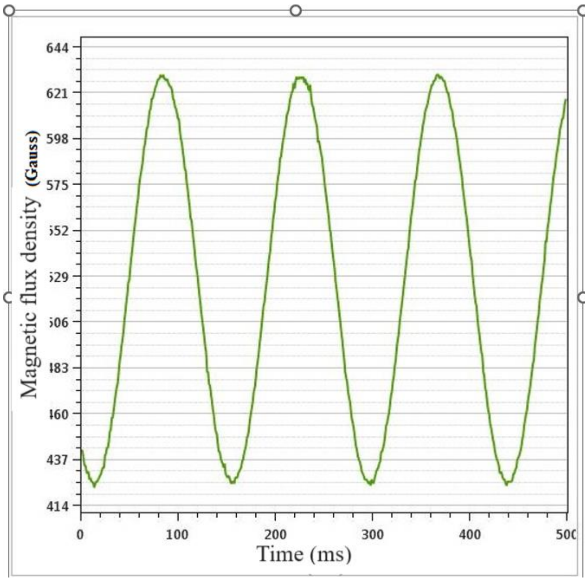

Figure 3 - Signal generated in the coil with a frequency of 5 Hz and amplitude of 5 V. with sample without treatment.

Figure 4 shows the signal after passing through the sample with treatment. In this, there is an increase in noise, because in addition to ferrite and austenite, there is the formation of the paramagnetic sigma (σ) embrittlement phase, from the ferrite structure.

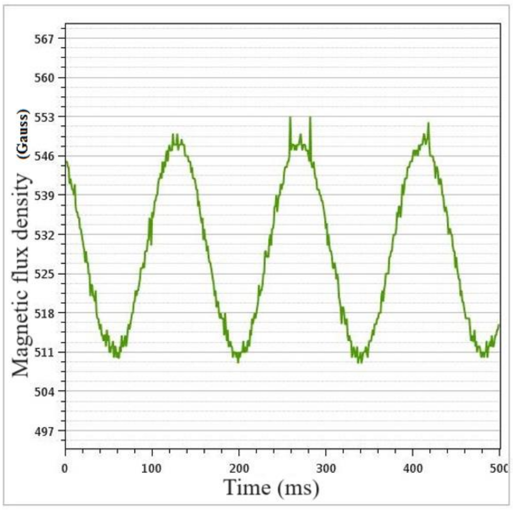

Figure 4 - Signal with noise after crossing the sample with treatment, with a frequency of 5 Hz and amplitude of 5 V.

Next, the study will be presented to determine the characteristics of the emitting wave capable of detecting the presence of the sigma phase, by analyzing the Barkhausen magnetic noise, in samples with a thickness of 8 mm. Figure 5 shows the RMS variation of the signal captured by the Hall sensor, as a function of the amplitude of the emitting wave applied to samples without precipitate and treated at a temperature of 850 °C for 15 min, for frequencies of 5 Hz and 50 Hz and amplitudes of 0.25 to 9 V.

It is observed in Figures 5 and 6 that the RMS values of the sample signal with treatment are lower than those of the sample without treatment. This can occur due to two factors: either the paramagnetism of the sigma phase or the blocking of the movement of the magnetic domains walls, as a result of the presence of this newly formed structure. In addition, a similar behavior is observed between the application of the two frequencies, that is, a parallel region up to around 0.5 V followed by an increase in the difference between 1 V and 2 V and finally close values from 3 V onwards.

The behavior observed in the 0.5 V region can be associated with the blocking of the movement of the domain walls, since the low-intensity magnetic flux is not enough to detect the presence of paramagnetism of the formed phase. However, in the region between 1 V and 2 V, as the magnetic flux is greater, the effect of paramagnetism becomes more sensitive, reducing the values, including a greater difference in RMS between the two samples, precisely because of the presence of precipitates in the treated sample. In the region above 3 V, as there is a large magnetic flux, there is an increase in the effect of Barkhausen magnetic noise, due to the movement of the magnetic domains walls, and this effect begins to overcome the paramagnetism of the sigma phase. In [8] tests were performed to measure the RMB in samples that did not undergo heat treatment and in samples that were subjected to treatment. The results of the measurements of the RMB observed for the samples that underwent a thermal treatment prove the occurrence of a decrease in the noise peaks due to the transformation of the ferromagnetic ferritic phase into a paramagnetic sigma phase.

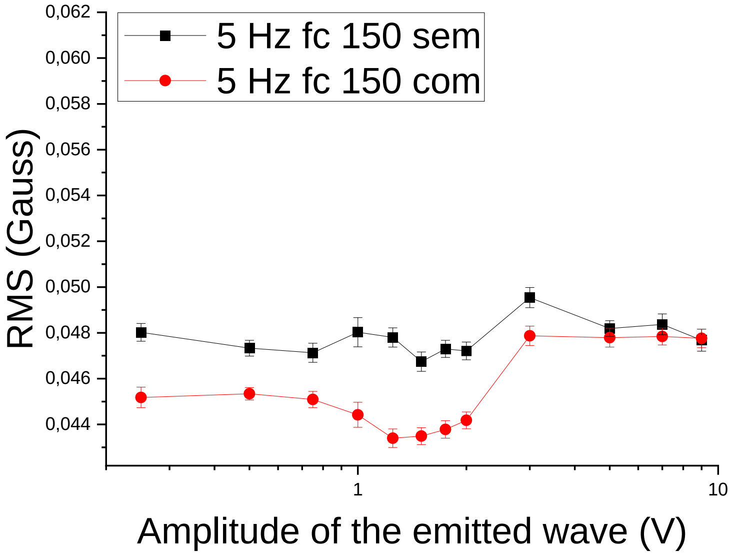

Figure 5 – RMS variation as a function of the amplitude of the emitting wave, for a frequency of 5 Hz and a high pass filter of 150 Hz, for samples with and without the presence of precipitate.

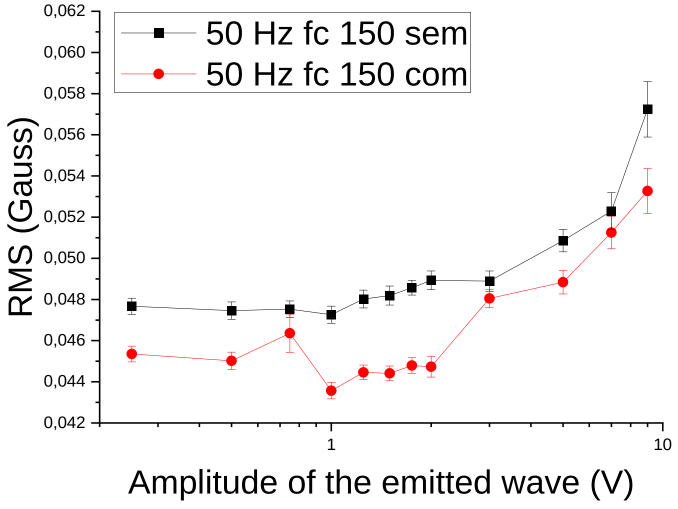

Figure 6 – RMS variation as a function of the amplitude of the emitting wave, for a frequency of 50 Hz and a high pass filter of 150 Hz, for samples with and without the presence of precipitate.

In order to visualize the best working region for this thickness, an analysis was performed using the difference in modulus of the RMS of the two conditions, with and without the presence of the sigma phase for the frequencies of 5 Hz, 10 Hz, 20 Hz and 50 Hz , as shown in Figure 7. The frequency of 50 Hz presents to 9 V condition at the same level of this region. This increase is due to the interference of the harmonics of the initial wave.

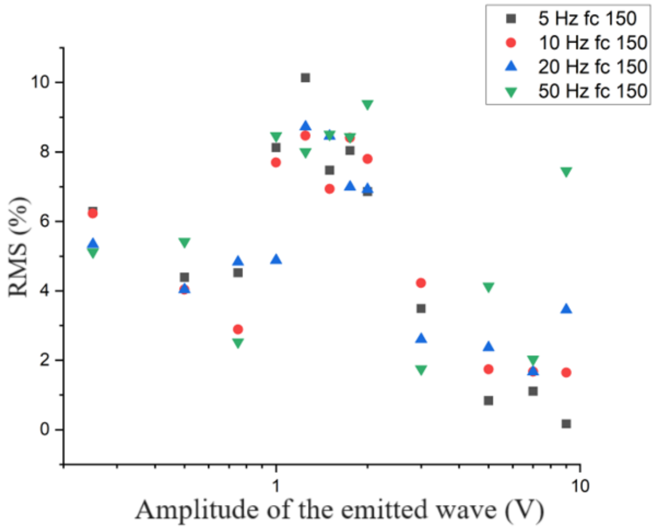

Figure 7 - Module of the RMS differencein percentage as a function of the amplitude of the emitting wave applied to the samples, for all frequencies.

4. Conclusions

The electromagnetic test carried out on the built bench was able to detect the presence of the sigma phase, with the replacement of the receiving coil by the Hall effect sensor.

The RMS values for the frequencies studied show lower values for the condition with precipitate, indicating that the effect of paramagnetism exceeds that of the Barkhausen magnetic noise for values of emitting wave amplitude up to 3 V.

The sample with a thickness of 8 mm and with the presence of the sigma phase presented three distinct regions of the RMS values, the first being up to amplitudes of the emitting wave of 0.75 V, the second between 1 V and 2 V and the third above 2 V, for the studied amplitudes. The best emitting waves were found in the amplitude region of 1 V to 2 V for all used frequencies. In this region are found the higher amplitude of measurements which facilitates the measurement and detection of the harmful constituent.

The electromagnetic test shows promise in monitoring structures in service, in order to determine the best time for intervention to avoid economic and personal damage to structures in the oil and gas sector. It ca be used in weld in order to check if it is correct.

References

1. S. S. M. TAVARES, et al. *Magnetic detection of sigma phase in duplex stainless steel UNS S31803*, *J. Magn. Magn. Mater*.**322** (2010) L29.
2. E. M. SILVA, A. M. R. PAULA, J. P. LEITE, L. S. S. ANDRADE, V. H. C. ALBUQUERQUE, J. M. R. S. TAVARES, *Detection of the Magnetic Easy Direction in Steels Using Induced Magnetic Fields*. *Metals - Open Access Metallurgy Journal*. **6** (2016) 12317.
3. E. M. SILVA, J. P. LEITE, F. A. FRANÇA NETO, J. P. LEITE, W. M. L. FIALHO, V. H. C. ALBUQUERQUE, J. M. R. S. TAVARES, *Evaluation of the Magnetic Permeability for the Microstructural Characterization of a Duplex Stainless Steel*, *Journal of Testing and Evaluation*. **44** (2016) 3 1106.

4. E. M. SILVA, A. M. R. PAULA, J. P. LEITE, L. S. S. ANDRADE, V. H. C. ALBUQUERQUE, J. M. R. S. TAVARES, *Detection of the Magnetic Easy Direction in Steels Using Induced Magnetic Fields*. *Metals - Open Access Metallurgy Journal*. **6** (2016) 317.
5. P. G. NORMANDO, E. P. MOURA, J. A. SOUZA, S. S. M. TAVARES, L. R. PADOVESE, *Ultrasound, eddy current and magnetic Barkhausen noise as tools for sigma phase detection on a UNS S31803 duplex stainless steel, Mater. Sci. Eng. A.* **527** (2010) 2886– 2891.
6. P. M. ORTIZ, J. A. P. BENÍTEZ, J. H. E. HERNÁNDEZ, F. CALEYO, N. MEHBOOB, R. GRÖSSINGER, 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.* **401** (2016) 108.
7. E. A. HUALLPA *et al*., *Use of Magnetic Barkhausen Noise (MBN) to Follow Up the Formation of Sigma Phase in SAF 2205 (UNS S31803) Duplex Stainless Steel, Materials Research*. **19**, (2016) 1008.
8. S. S. M. TAVARES, L. F. NORIS, J. M. PARDAL, M. R. DA SILVA, *Temper embrittlement of supermartensitic stainless steel and non-destructive inspection by magnetic Barkhausen noise, Engineering Failure Analysis*. **100** (2019) 322.
9. Y. HSIEH, L. ZHANG, T. CHUNG, Y. TSAI, J. YANG, T. OHNURA, T. SUZUKI, *In-situ transmission electron microscopy investigation of thedeformation behavior of spinodal nanostructured δ-ferrite in a duplex stainless steel, Scripta Materialia*. **125** (2016) 44.
10. B. Y. A. DUCHARNE, P. TENE DEFFO, S. H. TSAFACK, K. NGUEDJANG, *Directional magnetic Barkhausen noise measurement using the magnetic needle probe method, J. Magn. Magn. Mater.* **519** (2020) 111.
11. Y. HE, M. MEHDI, E. J. A. HILINSKIEDRISY, *Through-process characterization of local anisotropy of Non-oriented electrical steel using magnetic Barkhausen noise, J. Magn. Magn. Mater.* **453** (2018) 149–162.
12. S. KAHROBAEE, T. H. A. HEJAZI, *RSM - based predictive model to characterize heat treating parameters of D2 steel using combined Barkhausen noise and hysteresis loop methods, J. Magn. Magn. Mater.* **433** (2017) 131.
13. A. STUPAKOV, A. PEREVERTON, M. NESLUSAN, *Reading depth of the magnetic Barkhausen noise. I. One-phase semi-hard ribbons. ,. J. Magn. Magn. Mater.* **513** (2020) 123.
14. T. KALETI, C.H. GUR, *Determination of surface residual stresses in carburised AISI 8620 steel by the magnetic Barkhausen noise method, The British Institute of Non-Destructive Testing*, **62**, (2020) 416.
15. N. J. LEWIS, *et al*., *Development and application of measurement techniques for evaluating localised magnetic properties in electrical steel, J. Magn. Magn. Mater.* **452**, (2017) 233.
16. R. SILVA, C. L.KUGELMEIER, G. S. VACCHI, C. B. MARTINS JUNIOR, I. DAINEZI, C. R. M. AFONSO, A. A. MENDES FILHO, C. A. D. ROVER, *A comprehensive study of the pitting corrosion mechanism of lean duplex stainless steel grade 2404 aged at 475 ◦C, Corro. Scie.* **191**(2021) 109738.
17. X. XU, S. WESSMAN, J. ODQVIST, S. M. KING, P. HEDSTROM, *Nanostructure, microstructure and mechanical properties of duplex stainless steels 25Cr-7 Ni and 22Cr-5Ni (wt.%) aged at 325 °C, Mater. Scien. & Eng. A.* **754** (2019) 512.