MICROSTRUCTURAL CHARACTERIZATION OF CARBON STEELS USING ULTRASONIC VELOCITY MEASUREMENTS

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Abstract. *Non-destructive techniques are suitable alternatives for analysis and microstructural characterization of steels' phases. Based on this, this work aims to analyze the behavior of longitudinal and transverse ultrasonic velocities in three different types of AISI steels: 1006, 1080 and quenched 1045. These materials were selected due to their distinct microstructures: ferrite, pearlite and martensite, respectively. By measuring sound velocities for both longitudinal and transversal waves, the reference values were obtained for each steels' phase. The sound velocity in martensite is lower than the one in pearlite, and this one is lower than the sound velocity in ferrite. The differences in the values of the sound velocity arise primarily from dissimilarities in the values of the phases' elastic modulus which are affected by the degree of lattice distortion and misorientation. Thus, sound velocity measurements can be successfully used as a non-destructive technique to perform steels' microstructural characterization. Additionally to ultrasonic testing, the microstructures were characterized by metallography and hardness testing.*

Keywords: Non-destructive testing, AISI steels, Microstructure, Ultrasound velocity, Metallography, Hardness testing.

1. INTRODUCTION

The characterization of materials by ultrasound has some advantages in relation to traditional methods, which usually are destructive, relatively slow in results achieving, strenuous to operators and difficult to automate. Since the ultrasonic properties are affected by changes in the materials' microstructures, the use of this technique to determine the materials' mechanical properties may be awfully useful in many industrial applications.

According to the acoustic point of view, the materials often used in engineering are the most heterogeneous ones. An acoustic heterogeneity is characterized by a change in acoustic impedance (constant elastic and/or density) in the propagation medium. The most common differences in microstructures are due to grains' properties, inclusions, micro-cracks, precipitates, porosities and fibers (in the case of composite materials), Kruger (2000).

Because of interactions with the materials' microstructures, the variation of the wave propagation velocity and energy losses are the key factors in ultrasonic materials' characterization. In fact, these parameters can be used to determine the elastic modulus, microstructures, textures and mechanical properties, Berger (1992).

The main objective this work is to evaluate the performance of the sonic velocity in different microstructures, such as ferrite, pearlite and martensite, of the common steels AISI 1006, 1080 and water-quenched 1045, respectively. Measurements of ultrasonic velocities were performed using longitudinal, of 5 and 10 MHz, and transversal of 5 MHz, waves. To estimate the ultrasound velocity, a computational algorithm was developed, which applied the method of overlap echoes. This method is very versatile and relatively simply to implement, and gives accurate measurements for the velocity of ultrasonic waves. The referred accuracy arises from the fact that the implemented method can precisely measure the transition time from any cycle of one echo to the corresponding cycle of the next echo, Palanichamy et al. (1995).

2. EXPERIMENTAL PROCEDURE

It was considered samples of AISI 1006 (50.0x20.0x12.0 mm), AISI 1045 (Ø25.4x12.0 mm), and of AISI 1080 (50.0x20.0x12.0 mm) steels obtained from a plate, a circular bar and a rail train, respectively. To obtain the parallelism between surfaces, the samples were rectified until a thickness of 12 mm to an accuracy of ± 0.02 mm.

Initial ultrasonic and metallographic inspections on the samples did not show any porosity, inclusion, and other imperfections that may affect the experimental results.

Afterwards, the samples were austenitized based on the TTT diagram for the microstructure homogenization. The sample of AISI 1006 steel was heated to 940 °C and cooled in air. The sample of AISI 1080 steel was austenized to 780 °C and cooled slowly inside of a furnace to prevent the formation of other constituents different from pearlite. Finally, the sample of AISI 1045 steel was heated to 850 °C and then cooled quickly in water to obtain the martensite microstructure. The thermal treatments were accomplished using a MUFLA electric furnace with 1200°C of capacity.

The metallographic analysis was accomplished including the acquisition of images using a Jenaplan/Karl Zeiss optical microscopy.

For the hardness testing, it was considered the Vickers method using a pyramidal diamond penetrator with an angle of 136º and a load of 30 kgf. The testing was accomplished in five different points, and then the mean hardness value was obtained for each sample.

The measurement of the ultrasonic velocities was accomplished using a longitudinal and transverse wave transducer. The technique used was the pulse echo based on the direct contact with the sample. To measure the velocities of longitudinal waves, it was used a normal incidence transducer of 5 and 10 MHz and lubricating oil as coupling, and for the transverse waves was used a transducer of 5 MHz and honey as coupling.

To acquire the ultrasonic data was used a Krautkrämer USB12 device, connected to a Tektronix TDS3012B 100 MHz digital oscilloscope, which sends the ultrasonic signals to a computer where they were stored for future analysis.

To obtain the ultrasonic velocities, five signals were acquired and analyzed, considering two adjacent echoes per signal for each sample and for each frequency used. Then, using the computational algorithm based on echoes overlapping, the waves' time of flight between two echoes was computed. After obtaining the time of the wave propagation and knowing the sample's thickness, it was determined the average velocity of the wave propagation in the associated material, according to:

$$v = \frac{2X}{\tau_0}, \tag{1}$$

where X is sample's thickness and τ_0 is wave's time of flight. The value of τ_0 is calculated as being the value of τ, for $-\infty \leq \tau \leq \infty$, associated to the maximum value of, Normando (2008):

$$\left| \int_{-\infty}^{\infty} B1(t).B2(t-\tau)dt \right| \tag{2}$$

The time of the wave propagation can also be directly obtained from the oscilloscope device. However, it was used the echoes overlapping method, because it has higher sensitivity and guarantees maximum accuracy.

For the measurement of the elastic modulus (E) of each sample, initially their densities were calculated. For this, the samples were weighed using a digital balance of high precision and their volume was obtained by analyzing the water displacement in a Becker's volume. With the values of materials' densities and ultrasonic velocities of longitudinal and transverse waves, the elastic modulus was calculated based on the ASTM E 494-1995 norm (Measuring Ultrasonic Velocity in Materials) using the equation:

$$E = \frac{\rho V_T^2 \left(3V_L^2 - 4V_T^2\right)}{\left(V_L^2 - V_T^2\right)}, \tag{3}$$

where ρ is materials' density, V_T and V_L are transversal and longitudinal velocities, respectively.

3. RESULTS AND DISCUSSION

The microstructures of the samples considered were presented to qualitatively analysis of the principal microstructural factors that are more susceptible to interactions with the ultrasonic waves. In Figures 1, 2 and 3 are shown the optical micrographs of the AISI 1006, AISI 1080 and water-quenched AISI 1045 sample steels, that present ferrite, pearlite and martensite microstructures, respectively.

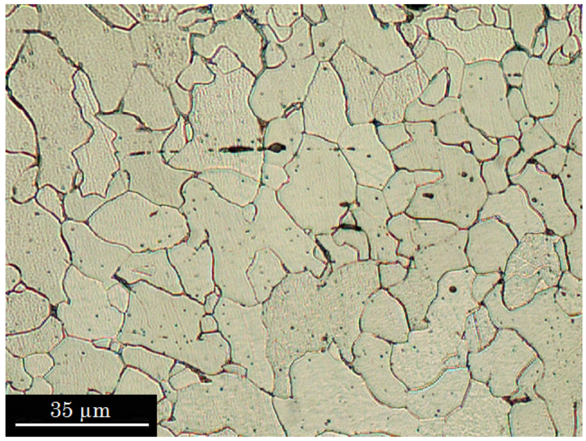

Figure 1. Optical micrograph of an AISI 1006 sample steel (etched with nital 3%).

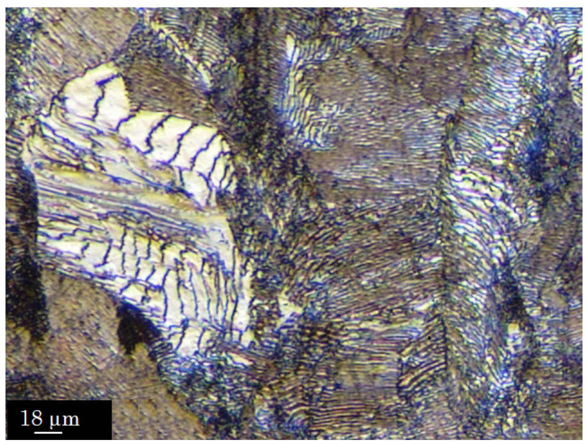

Figure 2. Optical micrograph of an AISI 1080 sample steel (etched with nital 3%).

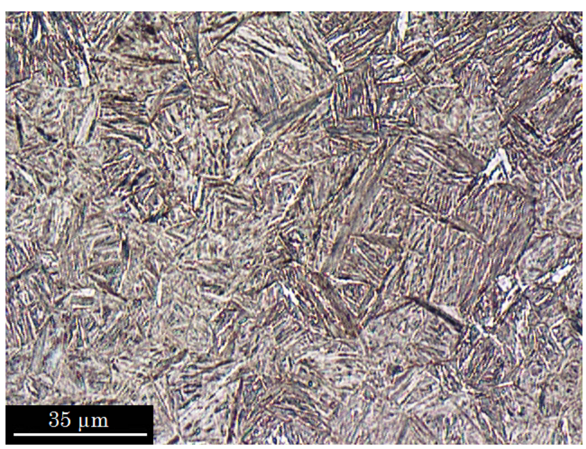

Figure 3. Optical micrograph of water-quenched AISI 1045 sample steel (etched with nital 3%).

Afterward, the results of the metallographic analysis were verified by hardness testing. Figure 4 shows the hardness values of different phases for the steel types considered. As expected, the microstructure that has the highest hardness value is martensite (814.12HV ± 47.00), followed by pearlite (317.09HV ± 27.58) and ferrite (101.64HV ± 39.31).

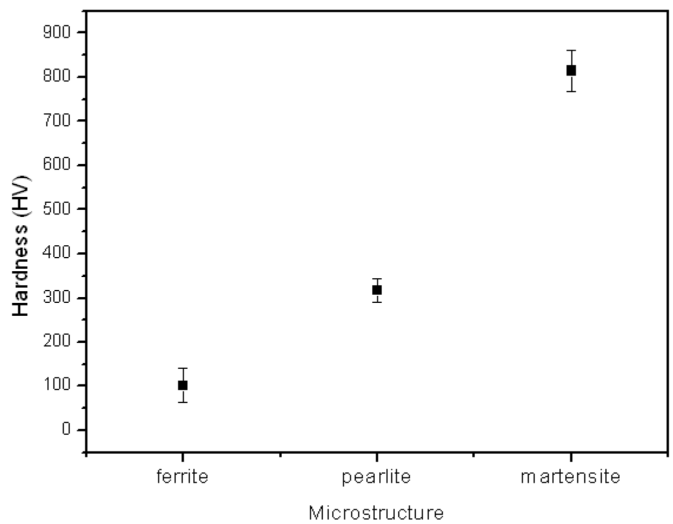

Figure 4. Results of Vickers hardness testing for the studied steels.

In Figures 5 and 6 are presented the variation of the longitudinal ultrasonic velocities in frequencies of 5 and 10 MHz, and transversal ultrasonic velocity in frequency of 5 MHz for the samples of AISI 1006, AISI 1080 and water-quenched AISI 1045 steels. As it was already referred, these values represent an average of five measures.

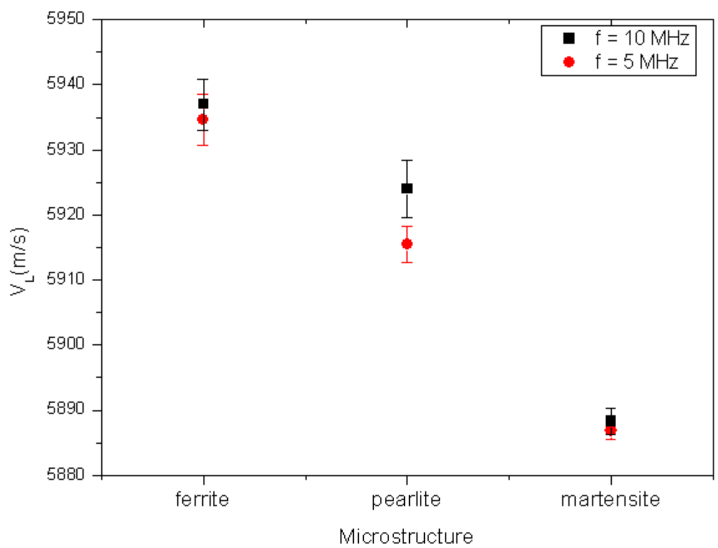

Figure 5. Correlation between microstructures and longitudinal ultrasonic velocities (V_L) in frequencies of 5 and 10MHz.

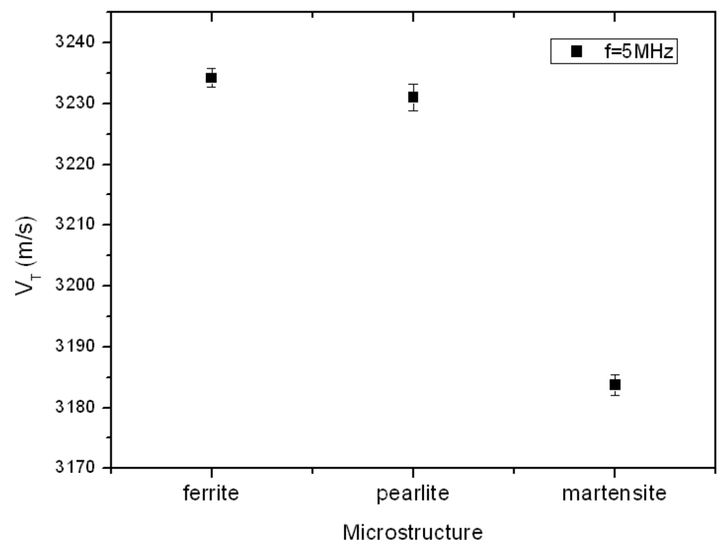

Figure 6. Correlation between microstructures and transversal ultrasonic velocities (V_T) in the studied samples with a 5 MHz frequency.

According to the obtained results for the longitudinal and transversal ultrasonic velocities' values, for 5MHz, it can be noted a higher velocity for the ferrite (5934.58 ± 3.88 and 3234.17 ± 1.49) and lower for the martensite (5886.84 ± 1.25 and 3183.73 ± 1.72), being the pearlite (5915.47 ± 2.85 and 3230.94 ± 2.19) with an intermediate value. This was observed for all considered frequency ranges. The results are in agreement with Hakan and Orkun (2005) and Papadakis (1963).

The lowest sound velocity in martensite can be explained by high amount of tetragonal lattice distortion. Martensite is the most random transformation product which results in an increase in the elastic anisotropy of the prior grain volume. Transformation starts at the austenite grain boundaries, and martensite plates feature different lattice orientation with respect to the parent austenite grains. Since austenite grain size determines the maximum dimension of the martensite crystals, excessive growth of austenite grains is avoided to obtain isotropic properties and small internal stresses.

The velocity in pearlite is immediately inferior to the one in ferrite due to an approximation of both in terms of density and elastic modulus, and also because of the large amount of ferrite phase that has approximately 67.5% of ferrite. According to Hakan and Orkun (2005), in the case of the specimens consisting of pearlite-ferrite, the main difference in the microstructure is the spacing of the cementite lamellae-ferrite, and content and size of ferritic phase. For all types of steels, sound velocity of fine pearlite-ferrite have been found lower than that of coarse pearlite-ferrite since the content and size of ferrite in fine pearlite-ferrite is low and the lamellae spacing is short compared to the coarser one.

After the measurements of the longitudinal and transversal wave ultrasonic velocities, was calculated the elastic modulus of each sample, considering the ASTM E 494-95 norm. These values are presented in Table 1.

Table 1. Elastic modulus obtained by ultrasonic pulse-echo testing.

Steel	Microstructure	Density [g/cm³]	Elastic modulus [GPa]
AISI 1006	Ferrite	7.766	209
AISI 1080	Pearlite	7.868	207
Water-quenched AISI 1045	Martensite	7.715	206

According to the ASTM E-494-05 norm, the results for the elastic modulus obtained by ultrasound testing have an error around 1% in comparison to the values obtained by mechanical testing. Additionally, regarding the reference EFUNDA (2008), the AISI 1006 and 1080 steels can present an elastic modulus value varying from 190 to 210 GPa.

Kim and Johnson (2007) using resonant ultrasonic spectroscopy measured the elastic modulus of ferrite, ferrite-pearlite, and martensite microstructures, being the obtained elastic modulus of 211.9, 210.3 and 203.5 GPa and the density values of 7.851, 7.835 and 7.709 g/cm³, respectively.

As the elastic modulus is directly proportional to the ultrasonic velocity, these values were already expected. The differences in the absolute values of the calculated elastic modulus for the samples considered may be due to the inaccuracy of the process used to determine the density ρ values.

4. CONCLUSIONS

A systematic approach to understanding the behavior of the ultrasonic velocity in different material microstructures has been presented in this work in theoretical and experimental means. For each material sample, it was accomplished the metallography analysis, the hardness testing, the measurement of ultrasonic velocities of longitudinal and transverse waves and calculated the elastic modulus. According to the results obtained, one can conclude the following:

(1) The highest ultrasound propagation velocity was observed for ferrite, then for pearlite and finally for martensite, both for longitudinal and transverse waves. This behavior was observed in all frequencies used. Ultrasound velocity is mainly affected by the changes in the elastic module of the individual grains that is dependent upon the degree of lattice distortion and misorientation in the prior austenite grains.
(2) The lowest ultrasound propagation velocity verified in martensite is due to the large amount of tetragonal distortion of the lattice that increases the elastic anisotropy of grains. In the pearlite case, the ultrasound velocity is essentially affected by the gills of Fe_3C carbon enriched. The value of the associated velocity is just below the velocity's value of ferrite due to an approximation both in terms of density and elastic modulus, and also because of the large amount of ferrite phase that has approximately 67.5% ferrite in the studied ANSI 1080 steel. The lower elastic modulus of the martensite is because for this phase was found the lowest values of sonic velocity and density.
(3) In general, the results obtained are promising and can make significant contributions within the characterization of materials and control of mechanical properties through non-destructive testing.

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