The Use of the Ultrasound Measurement Technique for the Evaluation of Mechanical Properties of the ASTM A36 Steels

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This work presents a study about the correlations between the characteristics of the acoustic waves and the mechanical properties of low carbon hot rolled steel bars, through the comparison between the wave velocity or attenuation and the tensile strength, yield point or elongation of the material. The aim is the possibility of using this technique to predict the production quality of ASTM A36 steels. Acoustic velocity and attenuation measurements by gain acquisition were carried out with the use of longitudinal waves and transducers of 5 and 15 MHz. Samples of hot rolled reinforcement steel bars with one inch diameter were used. A metallographic study of grain size and inclusion content was made along with chemical composition to verify the influence of these factors to the acoustic measurements. Results indicated that it is possible to use the presented methodology to estimate the mechanical properties, in especial, the tensile strength in steel rebars.
Keywords: *ultrasound, mechanical properties, steel, A36*

Introduction

The ASTM A36 standard (ASTM, 2008) indicates the basic requirements for the quality of raw material, chemical composition and strength for the production of structural steel. A range is established in which the tensile strength of the material shall be. Nevertheless, a minimum yield point and also elongation at break is required on the standard. To ensure that the steel produced follows the requirements, tensile tests are made by industry as a routine on samples of all heat productions.

To assure the requirements of the ASTM A36 standard, this work presents a study of the possible correlations between the acoustic wave characteristics and the low carbon hot rolled steel mechanical properties, through the comparison between the ultrasound velocity or attenuation and the tensile strength, the yield point, or the elongation of the material, enabling this technique as a lower cost alternative with greater agility for the properties verification of this material.

Nomenclature

Ec = *equivalent carbon content, mass %*
n = *number of data points*
TS = *tensile strength, N/mm²*
v = *velocity, m/s*
x = *variable x*
y = *variable y*
YP = *yield point, N/mm²*

Greek Symbols

Δl = *percent elongation, %*

Literature Review

It is known the possibility of measuring the mechanical strength of a material through the use of acoustic waves in the ultrasonic band (Tittmann, 1978). The application of this technique is based on the fact that the velocity and attenuation are directly affected by the microstructural characteristics of the analyzed material. Some characteristics of the steel that affect either the ultrasonic velocity or attenuation and, therefore, can be determined by this approach are: constituent phases; chemical composition; grain size; mechanical hardening; texture and the presence of residual stresses.

The variables of the ultrasonic inspection method include the characteristics of the produced wave (like the type of chosen waves, longitudinal or transverse) and the characteristics of the material to be inspected. The basic variables of the process should be adjusted to obtain better results on the tests.

The gain is a dimensionless value of the measure of the signal amplitude obtained in the test. The variation of the gain compensates for the sonic attenuation and can therefore be used in the analysis of the properties of materials as a quantity directly proportional to the attenuation. The gain adjustment is done to correct the height of the peaks representing the echoes with respect to the marked lines on the display of the apparatus.

For the analysis of the mechanical properties of steels the influence of the chosen frequency is not well established yet, and many authors only mention the frequency used, without further explanation. Fukuhara (1998), in his work with horizontally polarized transverse waves, used the frequency of 1.6 MHz to avoid the loss of wave energy that occurs for higher frequencies and the excessive enlargement of the beam that occurs at lower frequencies. Recent work (Vasudevan and Palanichamy, 2003) used three different frequencies – 2, 10 and 20 MHz – to measure the ultrasonic velocity in various processes of temperature aging for the cold-worked stainless steel and obtained a variation of only 0.5% in wave velocity for the same process, a variation within the error of the method.

To determine the mechanical properties of a material with the use of ultrasound it is necessary to know the characteristics of the material that may interfere with the behavior of the wave, and how each feature influences. The velocity and attenuation are the parameters that are modified and can, therefore, be used to estimate the material properties.

The characteristics of the steel that change the velocity or attenuation of the acoustic wave and can, therefore, be determined by this method are:

- present phases;
- chemical composition;
- grain size;
- inclusions;
- hardening;
- texture;
- residual stress.

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Since these characteristics influence the mechanical properties of steels, we can find a relationship between the mechanical strength and the characteristics of the wave.

Most published studies presents an empirical relationship between the behavior of the ultrasound and the characteristics of the analyzed material. This fact is due to the difficulty in separating the different factors that affect the velocity. In an early published study, Papadakis (1964) measured the ultrasonic velocity and attenuation for three different microstructures of steel, detecting the dependence of the velocity with the present phases.

The ASM Handbook (Bar-Cohen, 1992) presents the average sound velocities for metals of different chemical compositions and thermal treatments, and shows, with the exception of the magnesium, the inverse proportionality between the density and sound velocity.

Palanichamy (1995) presented the use of the ultrasound to estimate the grain size of an austenitic stainless steel. The author describes different methods on the attempt of determining the grain size, by the analysis of the ultrasonic backscattered signals, by the analysis of the attenuation of consecutive back wall echoes and by measuring only the first back wall echo for highly attenuating materials, obtaining an inaccuracy of less than 20% for the last method. Recent work (Prasad and Kumar, 1994) correlated the ultrasonic velocity with the percentage reduction (mechanical hardening) on the rolling process for steels with different thermal treatments.

The wave scattering caused by grain boundaries is strongly dependent on the relationship between the grain size and the wavelength of the ultrasound. When the grain size is smaller than 0.01 times the wavelength, the scattering is almost imperceptible, but if the grain size is 0.1 times the wavelength or greater, the wave dispersion can make the test impracticable. This is the origin of the grain size estimation through the measure of the sonic attenuation.

Using the acoustic resonance method described on his work, Ahn (1999) correlated the grain size of thermal treated low carbon steels with the velocity and attenuation, obtaining an accuracy of ±50 MPa. On his work, electromagnetic acoustic transducers were used.

Bouda published in 2000 a study correlating the hardness of the tempered low carbon steel with the sound attenuation and the ultrasonic velocity using longitudinal and transverse waves getting good results (Bouda, 2000). The samples were water tempered by the same procedure used to construct a Jominy curve. In this work, the velocity changes can be correlated with the amount of martensite present in each of their samples. The samples with higher martensite content presented a higher acoustic velocity. Bouda got greater sonic attenuation in positions with higher martensite content, assigning this fact to the higher amount of carbon, i.e., greater heterogeneity of the material. The author also presented in another study an attempt to correlate the grain size to the characteristics of the sound wave, but without good results (Bouda, 2003).

The hardening has an important influence on the propagation of the acoustic waves. Prasad and Kumar, in a study with cast iron (Prasad, 1994), correlated the ultrasonic velocity with the percentage reduction on the lamination of steels with different heat treatments. The study showed a decrease in velocity when increasing reduction, correlating this fact to the increase in material hardening. It was also observed a decrease in attenuation when increasing the degree of reduction. According to Prasad, the ultrasonic velocity is affected by dislocation density, and its increase causes a decrease in speed.

Experimental Procedure

Since this work was developed with the use of only one class of steel with low chemical compositional variation, and all samples were taken from the same rolling process, the factors that can influence the sound wave properties are reduced. The main metallurgical factors that can affect this study are the grain size and the inclusion content. The grain size, the inclusion content and the chemical composition were analyzed in order to verify possible compositional variations among different production heats. For these analyses, samples of hot rolled rebar with a diameter of one inch (25.4 mm) taken from 14 different production heats were used. The samples were labeled from 'A' to 'N'.

All the samples were cut in order to get three specimens with 100 mm length from each heat production. During the cut, great care was taken to reach a good parallelism between the opposite faces of the specimens to avoid measuring errors during the tests. These specimens were submitted to the ultrasonic analyses, when sound velocity and attenuation through gain analysis were measured, using transducers of 5 and 15 MHz. The chosen method for the testing was the pulse-echo with the use of compressional waves on the longitudinal direction of the samples, because it has easier application, fits well with the specimen dimensions and has shown good results in previous studies (Palanichamy, 2001; Bouda, 2003). All tests were performed with the use of liquid Vaseline as a couplant.

Analysis of chemical composition through Optical Emission Spectrometry were carried out to verify possible variations that can influence in the measure of the ultrasound characteristics, along with ASTM grain size analysis using the Heyn method described in the ASTM E112 standard, and inclusion analysis through the Method A – Worst Fields – described in the ASTM E45 standard. The grain size analysis was made on the transversal section of the specimens, while the inclusions content was carried out on the longitudinal section.

For the ultrasonic velocity measures, the length of the specimens were measured with the use of a digital caliper and this data was supplied to the ultrasound equipment, obtaining then, from the apparatus, the sound wave velocity. Five acquisitions were made for each of the three samples taken from the different heat production. To minimize the measurement errors due the sample was turned by 60° between each acquisition. With this procedure the average speed and its standard deviation were determined for each of the samples.

The attenuation measures were carried out indirectly, through the gain measure (remembering that the gain is directly proportional to the attenuation). For the attenuation measurements only the 5 MHz transducer was used, because of the better results in foregoing tests. The gain was calibrated for each analysis in order to adjust the first back wall echo peak to 80% of the CRT screen height, and its value was registered. To avoid operator's influence, an important error source on this measure, a constant weight was laid over the transducer. The attenuation measurements were taken according to the velocity measure procedure, i.e., five measures for each specimen, turning the specimen by 60° between two measures and calculating average attenuation and standard deviation for each three samples of each production heat.

Obtained the results of wave velocity and gain, this data were, then, compared with the data of tensile strength, yield point and elongation of the analyzed samples in a search of correlation among them. Graphic analysis and linear correlation analysis were performed, with the calculus of the cross-correlation coefficient, *r*, as defined by Eq. (1). This coefficient indicates the amount of correlation between any two quantitative variables independent of the units involved on each variable (Rodgers and Nicewander, 1988).

$$r = \frac{n\Sigma xy - \Sigma x.\Sigma y}{\sqrt{\left[n\Sigma x^2 - (\Sigma x)^2\right]\left[n\Sigma y^2 - (\Sigma y)^2\right]}} \quad (1)$$

The coefficient r varies from −1 to 1. A value next to 1 represents a well defined dependence between the two variables. In the same way, a value next to −1 represents a well defined inverse dependence. Values next to zero defines that there is no relation between the variables.

Results and Discussion

The chemical composition analysis by optical emission spectrometry and the grain size analysis are presented in Table 1. The table indicates the contents of carbon, silicon, manganese, phosphorus and sulfur, the main elements found on this grade of steel, along with the equivalent carbon content and the ASTM grain size. Figure 1 shows the representative microstructure of these steels.

The variation in the contents of the analyzed elements is reasonably low, indicating a well-controlled production system. The greater variation (greater standard deviation) for all samples was for manganese content, with a standard deviation of 0.044 from the average of 0.736%. Also, the grain size measured was consistently fine with value ranging from 14.1 to 11.9 μm (8.5 – 9.0 ASTM).

Table 1. Chemical composition of the steel samples and the ASTM grain size for each heat production.

Sample	C	Si	Mn	P	S	Ec	ASTM
	Values in mass percent (mass %).						
A	0.119	0.199	0.780	0.021	0.026	0.289	8.5
B	0.116	0.185	0.728	0.016	0.026	0.266	9.0
C	0.106	0.209	0.668	0.015	0.026	0.246	9.0
D	0.114	0.189	0.729	0.015	0.026	0.264	9.0
E	0.124	0.148	0.795	0.027	0.031	0.302	9.0
F	0.107	0.211	0.805	0.024	0.029	0.286	9.0
G	0.120	0.213	0.804	0.026	0.033	0.299	9.0
H	0.118	0.195	0.724	0.020	0.028	0.272	8.5
I	0.121	0.200	0.709	0.019	0.027	0.272	9.0
J	0.118	0.196	0.722	0.019	0.027	0.272	8.5
K	0.120	0.212	0.700	0.023	0.027	0.268	9.0
L	0.116	0.197	0.686	0.022	0.023	0.266	9.0
M	0.125	0.203	0.730	0.019	0.023	0.278	9.0
N	0.135	0.207	0.723	0.019	0.024	0.290	8.5
Average	0.119	0.197	0.736	0.020	0.027	0.276	
Standard Deviation	0.007	0.017	0.044	0.004	0.003	0.015	

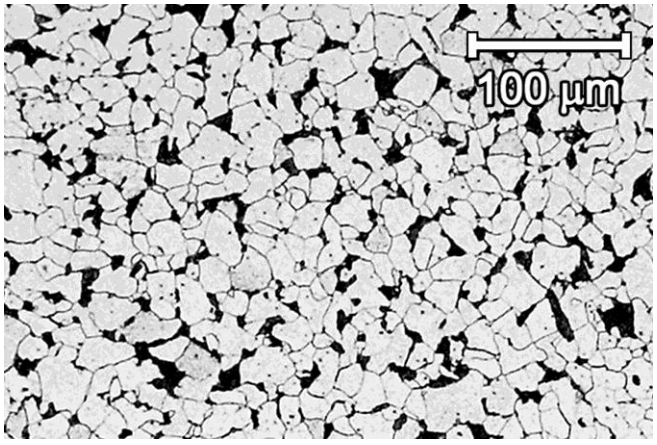

Figure 1. Optical micrograph representative of the analyzed steels. Etchant Nital 3%.

Table 2 shows the results for the inclusion content analysis. In general, the inclusion results have shown that the analyzed material had a good quality, considering the ASTM standard does not require greater controls with regard to level of inclusions. The samples that showed more severe degree of inclusion content were J, N and G for sulphide; F, D, J and C for silicates and G, M and F for oxides.

The acoustic velocities and gain are presented in Table 3. This data represents the average and standard deviation obtained from tests of three samples for each heat production. The values of gain are relative to a first measure, taken as a standard, and it explains some negative values.

Table 2. Inclusion content analysis through the method A – worst fields, described in the ASTM E45 standard.

Sample	Sulphides		Silicates		Oxides	
	Thin	Heavy	Thin	Heavy	Thin	Heavy
A	1.5	1.5	0.0	2.5	0.0	0.0
B	0.0	0.0	0.0	2.5	0.0	0.0
C	0.0	1.5	0.0	3.5	0.0	1.0
D	0.0	0.0	1.5	3.5	0.0	0.5
E	0.0	0.0	2.5	0.0	0.0	0.5
F	0.0	0.0	0.0	4.0	0.0	1.5
G	1.0	2.0	0.0	2.0	1.0	1.5
H	0.5	1.5	0.0	3.0	0.5	1.0
I	1.5	1.0	1.5	2.0	0.0	1.0
J	1.5	4.5	0.0	3.5	2.5	0.0
K	1.5	0.0	0.0	2.0	0.5	0.5
L	0.0	0.0	0.0	2.5	1.0	1.0
M	1.0	1.5	0.0	3.0	0.5	1.5
N	0.0	2.5	0.0	2.5	0.0	1.0

Table 3. Averages and standard deviations of acoustic velocities (m/s) and gain (dB) of the analyzed heats.

Production Heats	Vel. (5 MHz)		Vel. (15 MHz)		Gain (5 MHz)	
	Average	St. Dev.	Average	St. Dev.	Average	St. Dev.
A	5837.3	7.8	5865.8	0.3	-0.8	0.7
B	5821.8	11.0	5861.3	1.8	-2.2	0.4
C	5816.0	25.5	5866.8	2.8	-0.7	1.3
D	5819.7	1.0	5861.5	2.1	-2.4	0.6
E	5828.1	15.8	5867.0	7.1	+1.0	3.8
F	5834.4	3.2	5858.0	0.6	+1.0	0.7
G	5824.7	4.2	5854.1	0.4	-1.1	1.4
H	5840.5	9.4	5864.1	6.4	-1.6	0.1
I	5822.4	9.1	5859.4	0.3	-1.6	1.0
J	5844.5	4.5	5865.7	4.1	-0.2	0.0
K	5837.7	6.0	5864.7	4.9	-5.4	1.1
L	5830.2	11.0	5860.4	4.5	-4.3	0.8
M	5826.8	10.6	5864.9	0.1	-4.4	0.1
N	5838.1	2.8	5862.1	1.0	-3.6	1.1

Table 3 shows a greater standard deviation for the 5 MHz transducer, reaching 25.5 for velocity measure of sample C. However, this transducer has shown the best correlation results between material and wave properties, as can be seen in Fig. 2 and Fig. 3. Those figures show the tensile strength, yield point and elongation as a function of acoustic velocity with the use of 5 and 15 MHz transducers, respectively.

In the gain measures, it is observed a low standard deviation between samples, which characterizes a good reproducibility, but it does not guarantee accuracy on the results. The greater standard deviation for E and C heats indicates the error source from lack of parallelism of the opposite faces, once these heats obtain a greater standard deviation for velocity measures as well. The lack of parallelism of the specimen opposite faces influences the velocity and attenuation measurements in different ways. On the velocity determination, the lack of parallelism has influence on the bars length measures with caliper, softened by the acquisition of five measures, and on the measure of the ultrasound velocity itself, error which can be sometimes observed by the oscillation of the velocity measure between two fixed values. On the attenuation acquisition, there is only the measure error itself, once the caliper is not used.

In Fig. 2, a correlation coefficient of 0.84 was obtained between the velocity and the tensile strength indicating a direct proportionality between them. Equation (2) describes the linear regression showed in Fig. 2(A). The greater deviation from the regression of tensile strength vs. velocity was for sample L, with a deviation of approximately 13 MPa, and the deviation from the regression of yield point (Fig. 2(B)) was for sample C, with the same deviation of 13 MPa, which means that the method shows to be capable of estimating the tensile strength with accuracy of ±13 MPa. There was no correlation between the elongation and acoustic velocity.

$$TS = -7171.1 + 1.3v \tag{2}$$

In Fig. 3, the linear correlation coefficient of 0.10 for the tensile strength vs. velocity, −0.30 for yield point and −0.36 for elongation vs. velocity characterize an efficiency decrease of the test for a transducer of greater frequency (15 MHz). This was due to wave energy loses during the travel, as greater frequencies have greater energy loses during the wave travel (Bouda, 2003), resulting in better applications in minor thicknesses.

Figure 4 correlates the mechanical properties and the gain measures. It could be observed that the attenuation is better correlated with elongation. However, it is not a strong correlation. One explanation to this correlation could be the grain size influence in both elongation at fracture and attenuation. There is no correlation between gain and tensile strength or yield point.

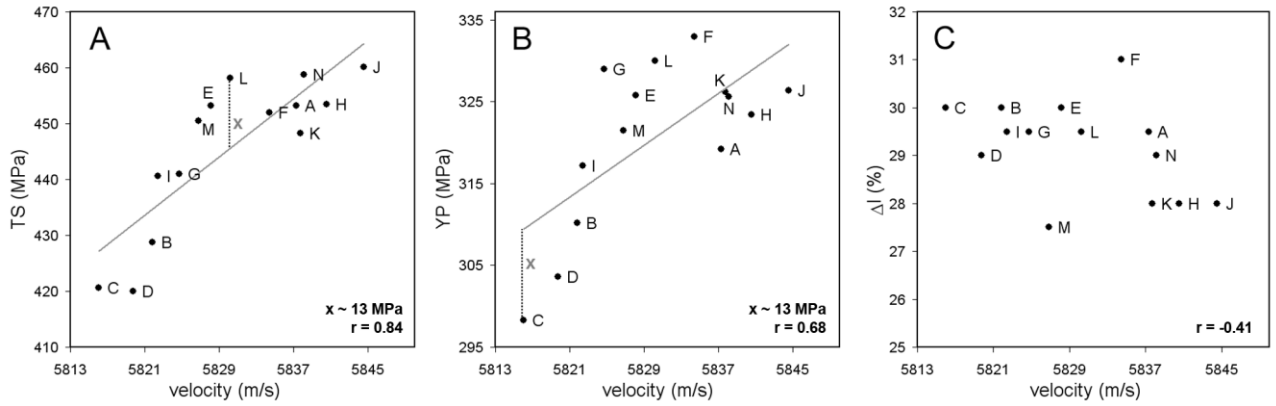

Figure 2. Acoustic velocity versus mechanical properties for 5 MHz transducer. (A) velocity *vs*. TS; (B) velocity *vs*. YP; (C) velocity *vs*. Δl. The dotted line 'x' represents the greater deviation from the linear progression, corresponding to approximately 13 MPa.

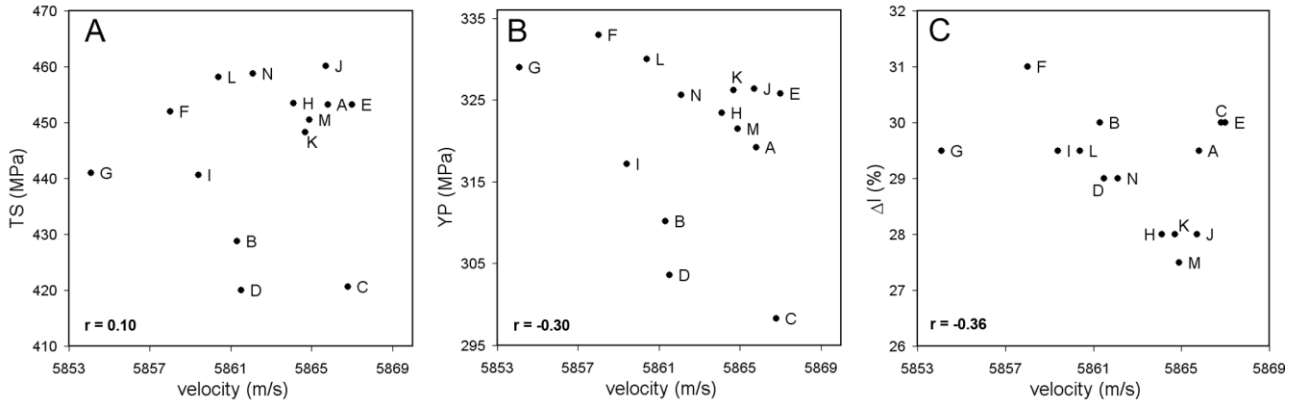

Figure 3. Acoustic velocity versus mechanical properties for 15 MHz transducer. (A) velocity *vs*. TS; (B) velocity *vs*. YP; (C) velocity *vs*. Δl.

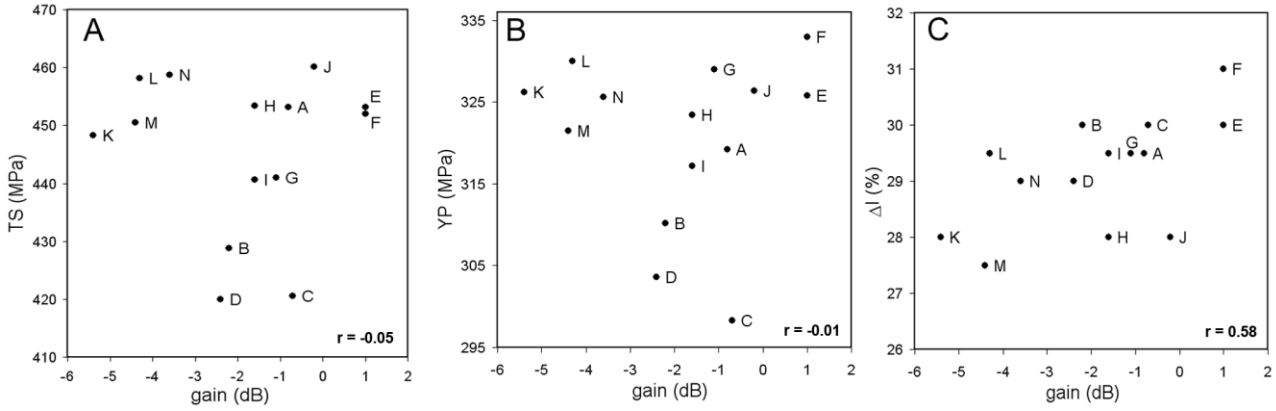

Figure 4. Gain versus mechanical properties for 5 MHz transducer. (A) gain *vs*. TS; (B) gain *vs*. YP; (C) gain *vs*. Δl.

Conclusions

The 5 MHz transducer showed to have more accuracy on the tensile strength determination, with a cross-correlation coefficient of 0.84.

A maximum deviation of 13 MPa on the values of tensile strength and yield point from the linear regression through the measure of the material acoustic velocity represents that this method can be considered, with further studies, as a method of non-destructive test for the measurement of mechanical properties of steels.

The greater error source of velocity and attenuation measures, causing differences among the five measures of each specimen, can be attributed to the lack of parallelism of the opposite faces, and a greater care must be taken to minimize this effect.

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