ANALYSIS OF THE BEHAVIOR OF Lcr WAVES PROPAGATING IN STELL BARS USING TAGUCHI METHOD

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Abstract. *The present work aims to develop experiments to determine the speed of propagation of ultrasonic waves in steel bars, based on conventional tools of quality - Taguchi and other techniques. The employment of Taguchi method is justified by the consequential reduced number of experiments with adequate results representing time-saving and cost reduction. An experimental design allowed the study of the influence of variables involved on performance assessment of the speed of critically refracted longitudinal waves (Lcr waves). The factors that influence the speed of ultrasonic wave were: temperature, force with which the transducer is in contact with the probe, applied stress on the bar and form of the transducers. The steel used was API 5L X70, to manufacture oil pipelines. Experiments were planned and executed using orthogonal array. We employed ultrasonic transducers and a portable pulser-receiver, as well as an embebed personal computer for data acquisition and analysis. An application in LabView™ was developed to acquire the signals and to analyze the results we used the program Minitab™. The propagation speed was obtained by measuring the travel time of the waves in a specially designed transducer assembly. The analysis identified the variables with significant influence, confirming that the control factors selected for the study may lead to improvements in the process.*

Keywords*: Ultrasound, Lcr Waves, Design of Experiments, Taguchi*

1. INTRODUCTION

Montgomery (2005) defined an experiment as a set of tests, in which, changes are made in the input variables of a process by observing and identifying the results of these changes in the response variables.

According to Barton (2001), experiments have a lot of information, requiring a statistical treatment of data to extract valuable findings. The design of experiments is a set of trials established on scientific and statistical criteria, ie, it is a technique used to define what, how much and in what conditions data must be collected during an experiment.

The methodology of design of experiments, as the name implies, is used to design experiments and to extract decisions with lower costs, less time and with statistical foundation.

Longitudinal critically refracted waves can be used to measure stresses, because the wave speed varies with the elastic properties and the stress in solids, mainly in metals. We call that acoustoelastic effect. Many factors influence the wave speed, besides the kind of material (Andrino, 2007). The most important environmental effect comes from the temperature.

Other influence factors are related to the way we create longitudinal waves propagating parallel to surface, which is using a shoe machined with a particular angle, the first critical angle. The form of the transducers and the force we use to place the transducers setup (probe) on the surface are the most significant.

The factor that clearly should influence is the stress applied to the sample. It is, in fact, what we really want to measure. So, we expect that the speed is influenced by that.

This work presents the application of a conventional and well-known tool of quality to evaluate if the factors identified are really significant when measuring stresses with Lcr waves. The Taguchi and other tools were employed, so the importance of each factor, in the range we tested, was analyzed.

Along the text we present a brief description about the types of design of experiments, the main concepts related to stress measuring with ultrasound, the experimental setup, the procedure applied, and the results we obtained, followed by the discussion and conclusions.

2. STRESS MEARUREMENT WITH L_{cr} WAVES

The critically refracted longitudinal wave, or L_{cr}, is the best type of ultrasonic wave for stress measurement. It spreads just below the surface, minimizing the effects of surface irregularities, such as corrosion. Its speed is more sensitive to changes in stress (Santos and Bray, 2000). To obtain the L_{cr} wave in steel, it is used a transducer for longitudinal waves on an acrylic base and the angle of incidence of the wave is about 28 degrees to the normal direction to the surface of the specimen tested, as shown in Figure 1.

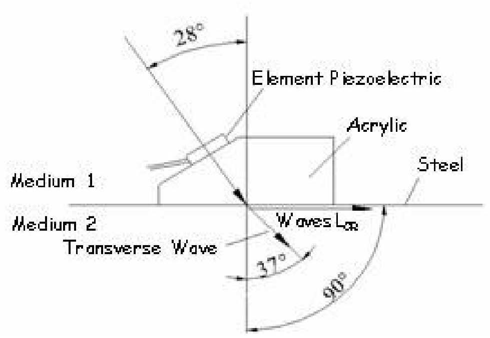


Figure 1. Generation of a critically refracted longitudinal wave (Andrino, 2003)

The ultrasonic techniques for measuring stress in materials are based on the behavior of the velocity of the elastic waves and they are related to the state of stress acting on a body. The speed of ultrasonic waves that propagate in the same direction as the applied stress is related to the state of triaxial deformation according to Eq. (1), (2) and (3) (Bray and Stanley, 1997).

$$\rho_0 V_{11}^{\ 2} = \lambda + 2\mu + (2l + \lambda)(\varepsilon_1 + \varepsilon_2 + \varepsilon_3) + (4m + 4\lambda + 10\mu)\varepsilon_1 \tag{1}$$

$$\rho_0 V_{12}^{\ 2} = \mu + (\lambda + m)(\varepsilon_1 + \varepsilon_2 + \varepsilon_3) + 4\mu\varepsilon_1 + 2\mu\varepsilon_2 - \frac{1}{2}n\varepsilon_3 \tag{2}$$

$$\rho_0 V_{13}^{\ 2} = \mu + (\lambda + m)(\varepsilon_1 + \varepsilon_2 + \varepsilon_3) + 4\mu\varepsilon_1 + 2\mu\varepsilon_3 - \frac{1}{2}n\varepsilon_2 \tag{3}$$

Where V_{11} is the speed of the particles in the same direction of wave propagation (longitudinal waves); velocities V_{12} and V_{13} represents the wave velocity in directions perpendicular to the particle motion (transverse waves); ρ_0 is the initial density; *l*, *m* and *n* are third order elastic constants (Murnagham's constants); the terms ε_1, ε_2 e ε_3 are components of deformation of the directions 1, 2 and 3; λ and μ are second order elastic constants (Lame's constants).

The Eq. (1), (2) and (3) can be simplified, considering that the deformation is acting only in the direction 1 (uniaxial state) and υ is the Poisson's ratio. Therefore, the following considerations can be made:

$$\varepsilon_1 = \varepsilon \tag{4}$$

$$\varepsilon_2 = \varepsilon_3 = -\upsilon\varepsilon \tag{5}$$

The Eq. (1), (2) e (3) can be simplified to:

$$\rho_0 V_{11}^{\ 2} = \lambda + 2\mu + \left[4(\lambda + 2\mu) + 2(\mu + 2m) + \upsilon\mu\left(1 + \frac{2l}{\lambda}\right)\right]\varepsilon \tag{6}$$

$$\rho_0 V_{12}^{\ 2} = \rho_0 V_{13}^{\ 2} = \mu + \left[4\mu + \upsilon\left(\frac{n}{2}\right) + m(1 - 2\upsilon)\right]\varepsilon \tag{7}$$

Deriving Eq. (6) in relation to deformation and regrouping terms, we obtain:

$$\frac{dV_{11}/V_{11}^{\ 0}}{d\varepsilon} = 2 + \frac{\mu + 2m + \upsilon\mu(1 + 2l/\lambda)}{\lambda + 2\mu} = L_{11}\,, \tag{8}$$

Where $V_{11}^{\ 0}$ is the speed of longitudinal wave when the material is free of stress. L_{11} is the acoustoelastic constant for critically refracted longitudinal waves in the direction of loading. Using Hooke's Law, a more suitable expression is obtained for the variation of stresses with the change in travel time of the wave:

$$d\sigma = Ed\varepsilon \Rightarrow d\sigma = \frac{E(dV_{11}/V_{11})}{L_{11}} = \frac{E}{L_{11}t_0}dt\,, \tag{9}$$

Where t_0 is the travel time of the wave when the material is free of stresses and dt is the variation of the travel time between two states of stress.

The variations in speed of an ultrasonic wave also depend on factors such as: temperature, force exerted by the support of the transducers on the piece, surface texture of the material, microstructure and residual stresses.

Studies show that the travel time of longitudinal waves propagating in a material presents a linear relationship with temperature (Santos, 2007), which is the focus of this study. Quantifying the influence of this factor allows the correct stress measurement, correcting the travel time using the knowledge of the temperature at which the material is.

According to Bray and Stanley (1997), the actual stress can be measured when Eq. (10) is used, which takes into account the effect of several factors.

$$\Delta\sigma = \frac{E\left(t - t_0 - \Delta t_{RS} - \Delta t_T - \Delta t_{TX}\right)}{L_{11} t_{ref}} = \frac{E\Delta t_F}{L_{11} t_{ref}} \quad (10)$$

$$t = t_0 + \Delta t_{RS} + \Delta t_T + \Delta t_F + \Delta t_{TX} \quad (11)$$

The term t_{ref} is the travel time of the wave at a reference temperature, with the material free of stresses. The term Δt_{RS} is the change in travel time of the wave due to residual stresses, the term Δt_T consider the fact that the temperature at which the test is performed is different from the reference temperature, the term ΔT_{TX} considers the effects of texture material, as in the case where there is corrosion, or when it has anisotropic properties. Finally, Δt_F is primarily the effect that we want to calculate, caused by the variation of an external force to the material.

3. DESIGN OF EXPERIMENTS (DOE)

DOE is a technique used to plan experiments, ie, to define what, how much and under what conditions data should be collected during a given experiment, seeking basically meet two major goals: the statistical accuracy in the response and the lowest possible cost. Through it, researchers can determine the variables that most influence the performance of a particular process, that results in: (i) reduction of process variation and better agreement between the nominal values obtained and the desired values, (ii) reduction of process time and operating costs and (iii) improving process yield.

Our objective is to evaluate the effect of influence factors on the behavior of the propagation speed. One way to perform that, it is to measure the travel time under each different configuration of the test. If the distance travelled is kept constant, the propagation speed is proportional to the travel time. The controllable factors considered important to perform optimization analysis of the experiment were: (a) temperature, (b) force with which the transducer is in contact with the probe; (c) stress applied to the bar, (d) form of transducers. For each factor we selected two levels (low and high), presented in Table 1. These levels were chosen building on the parameters commonly used in ultrasonic testing.

Table 1. Input variables

Factors	Selected Levels	
	Low (1)	High (2)
A: Temperature (ºC)	20	25
B: Force (N)	45,1	115,8
C: Stress (MPa)	20,1	40,4
D: Form (inches)	0,5	1,0

3.1. Temperature

The temperature of the part is reported to have great influence on the travel time of L_{cr} waves (Fraga et al., 2008) and therefore must be well controlled so there are no losses in the measurements. In order to maintain the room temperature constant, some procedures were performed for monitoring the temperature of the bar during the experiment. With the aid of a thermocouple (type *k*) and a signal conditioner, we managed to keep the temperature on the level 1 around 20 °C, with values ranging from 19.79 °C to 20.25 °C and level 2 around 25 ºC, with values ranging from 24.81 °C to 25.03 °C.

3.2. Force between the probe and the surface

The travel time is very sensible to variations of the distance between the shoes. So, if the probe weight is not controlled or if the force applied to guarantee the contact among the shoes and the surface is not constant, the distance and position of the shoes can vary. In order to study the effect of such variations we used four objects, which we placed over the probe, as shown in Figure 2.

Figure 2. Weights used to stabilize the force on the probe

The force levels we chose had two configurations. The first configuration was adopted for the two smaller blocks and in the second configuration, it was used the four blocks. Table 2 shows the weight of all blocks and the two configurations adopted.

Table 2. Weight of the blocks and configurations

Block	Mass [kg]	Weight Force [N]	Configuration 1	Configuration 2
1	2,3	22,6	x	x
2	2,3	22,6	x	x
3	3,2	31,4		x
4	4,0	39,2		x
Weight Force [N]			45,1	115,8

3.3. Stress applied to the steel bar

To apply the acoustoelastic theory, the material must be in its elastic regime, in which the deformation is related to the stress across the Young's modulus of the material (Hooke's Law). Aiming to achieve a stress value that did not cause damage to the system we adopted, the tensions should be not only below the nominal value supported by the equipment, but also within a variation that did not damage the sample. The bar we used as a sample can not undergo plastic strain, ie stresses greater than the yield stress, which is about 480 MPa in this case. The material is API 5L x70 steel, used in pipelines.

From the readings in a manometer at the manual pump used, we calculated the resultant force on the bar and, subsequently, the stress in the center of the bar. The final stress at the center of bar corresponds to about 25% of the yield strength of the material, as Table 3. A study was carried through CAE (Computer Aided Engineering) in Pro-Engineer/Pro-Mechanica® 2.0 software, to investigate possible stress concentrators able to raise the probabilities of reaching the plastic regimen in the part.

Table 3. Pressure applied at the pump and expected values of tension and force resulting in bar

Applied pressure at pump [MPa]	Resultant force in the bar [N]	Stress in the center of the bar [MPa]
2,5	14137,2	20,1
5,0	28274,3	40,4

3.4. Form of transducers

The transducer is one of the most critical components of any ultrasonic system. The Panametrics brand chosen for the ultrasonic transducers used in this study have the natural frequency of 5 MHz, with different shapes, ie, size of the piezoelectric element, as showed in Figure 3.

(a) Model A406S - 5 MHz - 0.5" x 0.5"   (b) Model A405S - 5 MHz - 0.5" x 1"
Figure 3. Rectangular ultrasonic transducers

4. ASSEMBLY OF THE EXPERIMENTS

The experimental setup is shown in Figure 4. The set consists of:

1. A PXI 1031 DC industrial computer equipped with a data acquisition board PXI-5114, both from National Instruments™, installed with a monitor, keyboard and mouse;
2. A signal conditioner SCC-68, also from National Instruments™, used to measure the temperature;
3. A probe consisting of two transducers to generate longitudinal waves mounted to acrylic shoes and joined using a small bar of steel, to keep the distance constant;
4. A portable pulser/receiver USB UT350 brand Ultratek™ coupled to transducers;
5. A traction device;
6. Hydraulic cylinders (RMCW200 model), used to apply loads to the bar of steel;
7. A hydraulic hand pump with a digital manometer (PW39);
8. A bar of steel API 5L X70, with thermocouple attached to its upper surface geometric center.

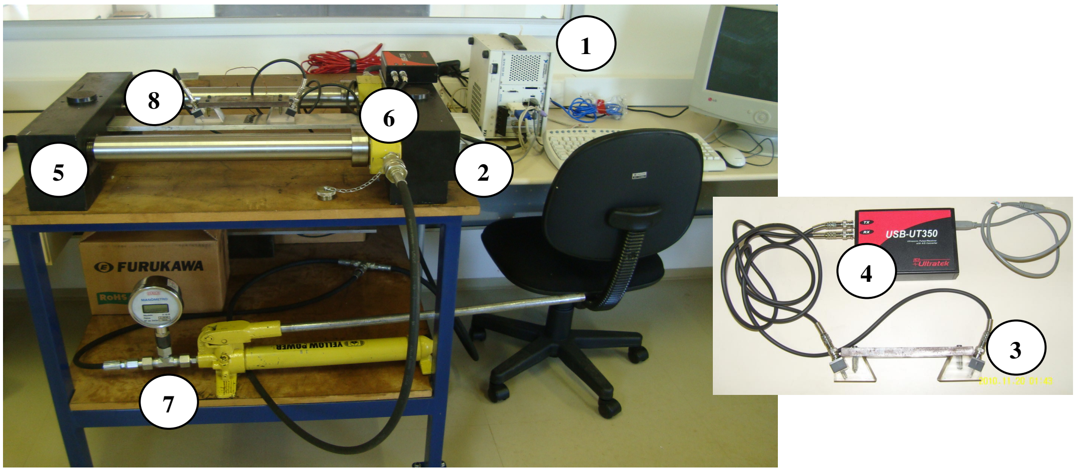


Figure 4. Complete assembly of the equipment for the experiments

5. RESULTS

The experimental planning for this work was defined as a full factorial design 2^k, with $k = 4$, resulting in 16 trials, so the Planning Matrix has two levels and four factors (Table 4). Each test was repeated five times (R1 to R5), totaling 80 results. The repetitions enable the use of hypothesis testing in statistical analysis, which is not the case, but also allow us to estimate the dispersion. Table 5 presents the results of the repetitions, including the averages and standard deviations of the propagation speeds for each test. The numbers are in parenthesis in Table 4 and Table 5 and they refer to the order in which was performed the experiments, this order was obtained by the software Minitab™.

Table 4. Planning matrix

Experiment (order)	Factors			
	A (ºC)	B (N)	C (MPa)	D (inches)
1 (10)	20	45,1	20,1	0,5
2 (1)	25	45,1	20,1	0,5
3 (15)	20	115,8	20,1	0,5
4 (6)	25	115,8	20,1	0,5
5 (13)	20	45,1	40,4	0,5
6 (14)	25	45,1	40,4	0,5
7 (2)	20	115,8	40,4	0,5
8 (3)	25	115,8	40,4	0,5
9 (9)	20	45,1	20,1	1,0
10 (16)	25	45,1	20,1	1,0
11 (7)	20	115,8	20,1	1,0
12 (12)	25	115,8	20,1	1,0
13 (4)	20	45,1	40,4	1,0
14 (5)	25	45,1	40,4	1,0
15 (11)	20	115,8	40,4	1,0
16 (8)	25	115,1	40,4	1,0

Table 5. Results of five repetitions for the propagation speed of waves

Experiment (order)	A	B	C	D	R1 (m/s)	R2 (m/s)	R3 (m/s)	R4 (m/s)	R5 (m/s)	Mean (m/s)	Standard Deviation (adm)
1 (10)	1	1	1	1	5948,3	5949,1	5949,1	5949,1	5949,1	5948,94	0,36
2 (1)	2	1	1	1	5932,7	5932,7	5932,7	5933,7	5933,7	5933,10	0,55
3 (15)	1	2	1	1	5953,7	5954,6	5954,6	5954,6	5954,6	5954,42	0,40
4 (6)	2	2	1	1	5937,3	5939,1	5940,0	5937,3	5938,2	5938,38	1,17
5 (13)	1	1	2	1	5947,3	5948,7	5948,2	5948,2	5947,3	5947,94	0,61
6 (14)	2	1	2	1	5933,8	5932,7	5931,8	5931,0	5930,9	5932,04	1,22
7 (2)	1	2	2	1	5951,9	5952,8	5951,9	5952,8	5952,8	5952,44	0,49
8 (3)	2	2	2	1	5937,3	5938,2	5936,4	5936,4	5936,4	5936,94	0,80
9 (9)	1	1	1	2	5962,0	5961,0	5961,0	5962,0	5961,0	5961,40	0,55
10 (16)	2	1	1	2	5940,5	5940,5	5941,4	5941,0	5942,3	5941,14	0,75
11 (7)	1	2	1	2	5965,7	5965,6	5965,6	5962,4	5962,4	5964,34	1,77
12 (12)	2	2	1	2	5945,5	5944,2	5945,0	5945,0	5945,5	5945,04	0,53
13 (4)	1	1	2	2	5960,1	5960,1	5961,0	5961,0	5961,0	5960,64	0,49
14 (5)	2	1	2	2	5941,4	5941,4	5941,4	5941,4	5942,3	5941,58	0,40
15 (11)	1	2	2	2	5965,7	5965,6	5965,7	5965,6	5962,4	5965,00	1,45
16 (8)	2	2	2	2	5943,2	5944,1	5944,2	5944,2	5945,1	5944,16	0,67

6. ANALIZYS OF THE RESULTS

The following items present the analysis of experiments using the Minitab™ by control chart (R), box plots, Pareto chart, and the p-value. We performed the analysis of the effects of influence variables and of the interactions between the variables of influence. Besides, we analyzed the results using the signal-to-noise ratio of Taguchi.

6.1. Analysis by control chart

The analysis by the control chart is used to evaluate the process statistics over time and detect the existence of special causes, through the standard deviation. If the process is under control and is functioning within specification limits, the control chart will show that all points are within the control limits, defined by the red lines, representing a reliability of 99%. It follows from Figure 5 that the experiment is under control because there is no result above or below the line of control (Santos, 2009).

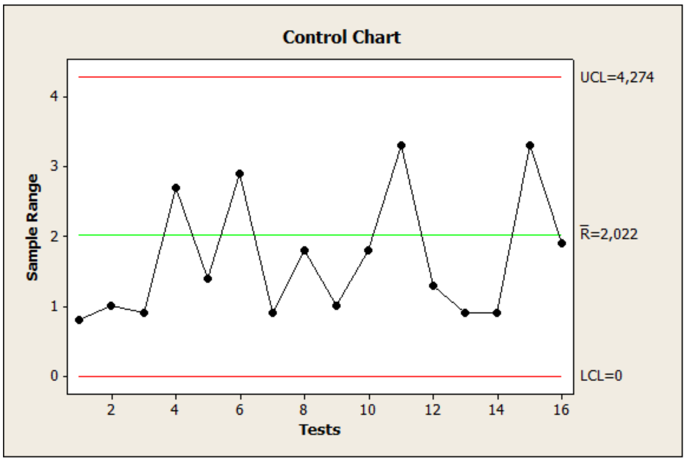
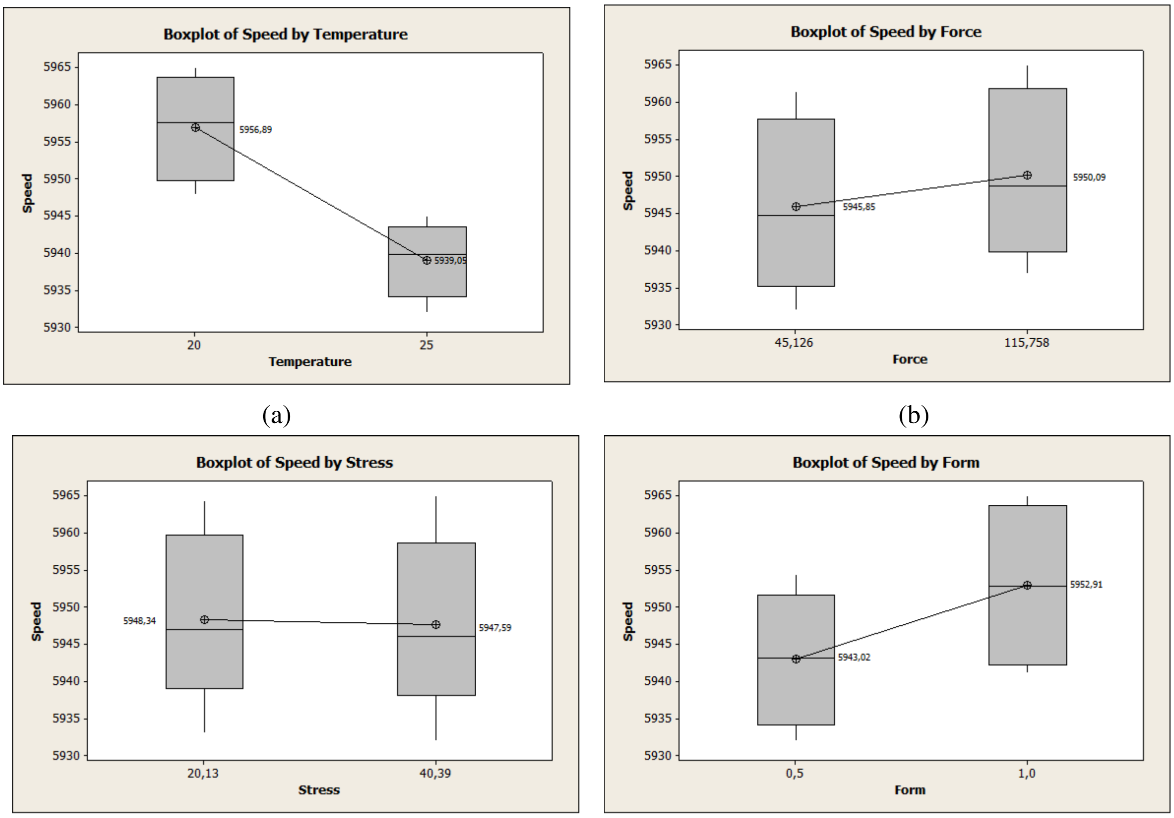


Figure 5. Control Chart (R) for the propagation speed of waves

6.2. Analysis of the mean and variance of speed through charts box

Both the mean and standard deviation may not be adequate measures to represent a set of values, since they are affected significantly by extreme values. To solve these problems we can use the Boxplot (charts box), which present the results through rectangles constructed with the quartiles and provides information relating to extreme values. Quartiles are values that divide a sample of data into four equal parts, called Q1 (25%), Q2 or median (50%) and Q3 (75%). With these quartiles is possible to analyze the dispersion and central tendency of a data set. The box plots indicate that the propagation speed undergoes variation with all variables of influence, as Figure 6.



(a) (b) (c) (d)

Figure 6. Analysis of the speed charts for charts box

The interquartile range is the distance between the first and third quartiles shown in Table 6.

Table 6. Values for the quartiles

Temperature (ºC)	Q1	Q2	Q3	IQ
20	5949,82	5957,53	5963,61	13,79
25	5934,06	5939,76	5943,52	9,45
Force (N)	Q1	Q2	Q3	IQ
45,1	5935,11	5944,76	5957,72	22,60
115,8	5939,83	5948,74	5961,86	22,03
Stress (MPa)	Q1	Q2	Q3	IQ
20,1	5939,07	5946,99	5959,66	20,59
40,4	5938,10	5946,05	5958,59	20,49
Form (inches)	Q1	Q2	Q3	IQ
0,5	5934,06	5943,16	5951,57	17,50
1,0	5942,23	5952,84	5963,61	21,38

It follows from Figure 6 and Table 6 that the temperature of 25 °C, the force of 115.8 N**,** the stress of 40.4 MPa and shorter form of the transducers show less variation around the average value found, with an interquartile range (IQ) or a variation of 9.45, 22.03, 20.49 and 17.50 respectively, as illustrated in Table 6. In conclusion, these levels for the factors analyzed, show a smaller dispersion of results.

6.3. Analysis through the Pareto chart and the p-value

This analysis was developed in order to evaluate which of the four variables have significant influence on the results, determining the magnitude and importance of effects. The Pareto chart shows the absolute value of effects and build a reference line, called line Lenth, represented by a red line value of 2.31 (Figure 7). Any effects that extend beyond the reference line are significant at the standard and significantly important for this analysis. We used in a significance level alpha of 0.05, a value which is the usual pattern. It means 95% of confidence that the factor influences the speed.

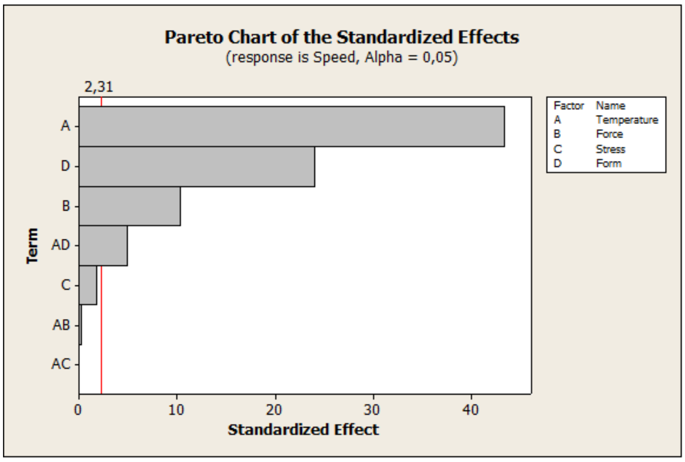


Figure 7. Analysis of the speed variation by Pareto chart

Looking at the Pareto chart, from Figure 8, the temperature (A), the form of transducers (D), weight on the probe (B) and the interaction between temperature and form (AD) have significant influence on the propagation speed of Lcr wave. In addition to this analysis, it is possible to evaluate the influence of variables on the results of speed through the p-value. The p-value ranges from 0 to 1 and the lower the p-value, the greater the chance that an effect is statistically significant for the study. Table 7 presents the p-value for variables of influence and their respective interactions.

Table 7. P-values method applied to the speed variation

Terms	P-value	Terms	P-value
Factor A	0,000	Interaction AB	0,855
Factor B	0,000	Interaction AC	0,967
Factor C	0,104	Interaction AD	0,001
Factor D	0,000		

The factors A, B, D and AD interaction have significant influence on the results of the propagation speed, since the values related to the p-values are smaller than the specified significance. The C factor and the interactions between AB and AC do not show significant influence on the results of the propagation speed, since the values related to the p-values are greater than the specified significance. From this analysis, both the Pareto chart as the p-value show that they are the same variables that significantly influence the results of the propagation speed.

6.4. Analysis through the effects of influence variables

Figure 9 shows the graph comparing the magnitudes of the effects of four influence variables in the results of the propagation speed of waves. It is possible to evaluate the influence of a major effect on the averages of results. Analyzing the behavior of propagation speed as a function of temperature, it is possible to observe the effect of this variable, a significant decrease in the response variable (propagation speed) as the temperature increases. Performing an analysis of the behavior of the propagation velocity as a function of force applied during the test and the shape of transducers, it is possible to observe that the effect of these variables is a significant increase in the response variable. The analysis of the propagation speed as a function of stress shows no significant variation.

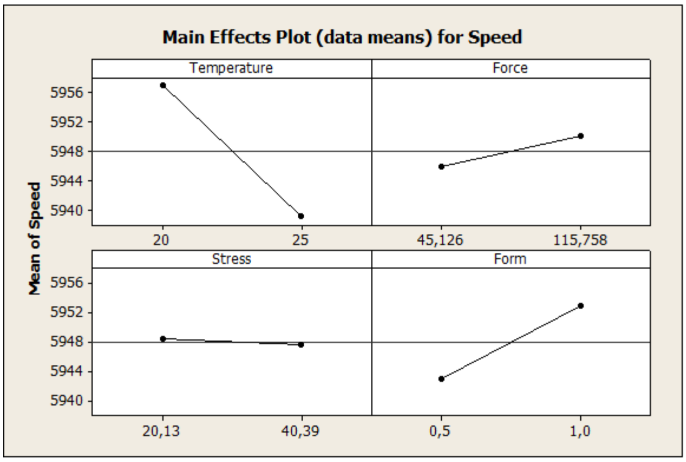


Figure 9. Graph of the effects of variables

6.5. Analysis through interactions between the variables of influence

The graphs of interactions show how the effect of one factor depends on the level of other factors. An interaction between factors occurs when the change in response from low level to the highest level of a factor is not the same as the change in response at both levels of a second factor, ie the effect of one factor depends on a second factor. The starting point for analysis of the results presented in these graphs is the observation of a parallel line. The parallel lines on a graph of interaction indicate no interaction. The greater the difference in slope, the greater the interaction. Since the interactions may increase or decrease the main effects, it is extremely important to evaluate them (Figure 10).

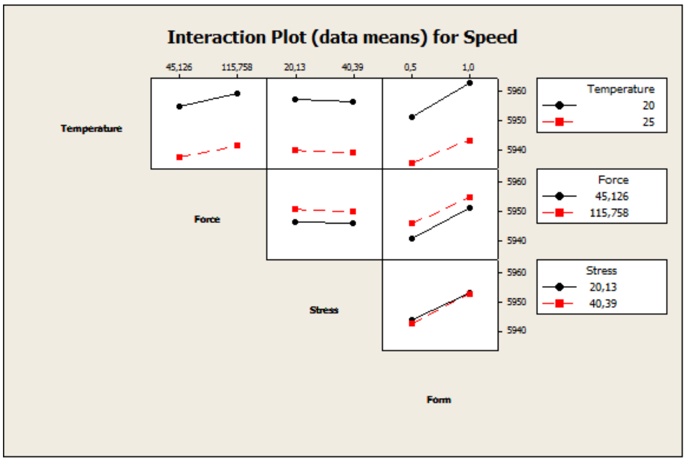


Figure 10. Graph of interaction between variables

The interaction between temperature and force, temperature and stress, force and stress and between force and form of transducers do not present any change in response from low to high level of a factor, when compared with the increase in low level to the high level of another factor, indicated by the presence of parallel lines, ie no interaction between these factors. Analyzing the interaction between temperature and form of transducers there is a slight difference in the slope of the line when compared with the higher level of temperature. The interaction between stress and form shows a slight tendency to increase the propagation speed, what can be viewed when observing the results with the higher level of stress and form of transducers, ie, the lines are not parallel. It can be concluded that the interaction between temperature and form of transducers and interaction between stress and form of transducers has a higher degree of interaction, although not so high.

6.6. Analysis by Taguchi

This analysis seeks to find levels of the factors that minimize the variation in response, while adjusting, or maintaining, the experiment on the target. The analysis allowed one to find an optimal combination of levels of controllable factors that reach robustness against noise factors. One way to know the variation cause by noise factors is by analyzing the signal to noise ratio. It is part of a technique that seeks to manipulate factors that presents variability caused by noise. Higher values of signal to noise ratio (S/N) indicate the settings of control factors that minimize the effects of noise factors, as Figure 11.

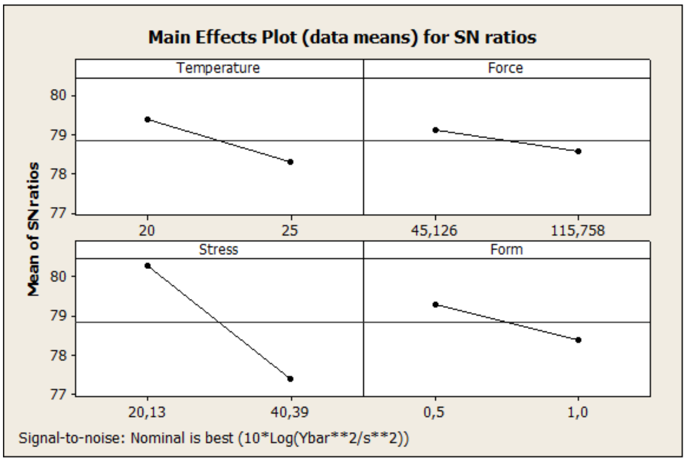


Figure 11. Graph of Taguchi

From Figure 10 it is possible to identify the set of variables that reduce the variability of the speed of propagation. The best combination is with 20 ºC, 45.1 N, 20.1 MPa and 0.5 inches, identified by the highest values of signal to noise ratio. Figure 11 allows us to see that the factor C - stress - is the most influential in the signal to noise ratio, because its slope is greater, indicating that it is the factor which brings more noise to the speed.

7. CONCLUSIONS

This study aimed to evaluate the variables: temperature, force with which the transducer is in contact with the probe, the stress applied on the bar and form of transducers, and their influence on the speed of ultrasonic waves. The determination of the speed of ultrasonic waves in steel bars is necessary to evaluate the stresses, according to the acoustoelastic method. First, we created a design of experiments incorporating the factors that directly influenced the results. The plan was followed, with the characterization of the performance parameter, the testing and analysis of results. The results allow us to identify the influence of the factors on the propagation speed of L_{cr} waves, and identify a set of parameters that gave the best results and lower dispertion, according with Taguchi method.

It could be observed through DOE analsys that: (a) Examining the control chart (R): the experiments are under control, because there is no result above or below the control lines; (b) Using the box plot graph and quartiles: the values for the influence factors that causes smaller variation in the speed were 25 °C, the force of 115.8 N, the stress of 40.4 MPa and form of the transducer of 0.5 inches; (c) The Pareto chart and the p-value showed that the variables that exert significant influence on the speed propagation of wave are temperature, force, form and interaction between temperature and form of transducers, the stress factor and interactions between temperature and force and between temperature and stress do not exert a significant influence on the results; (d) The analysis through the graph of the effects of influence variables showed that the temperature, the force and form transducers significantly influence the results of the propagation speed; (e) Through the analysis of interactions between variables in the average propagation speed we concluded that the interaction between temperature and the form, and interaction between the stress and the shape has a higher degree of interaction; (f) The Taguchi method showed that the optimal configuration which reduces the amount of variation of the speed is the combination of 20 ºC, 45.1 N, 20.1 MPa and 0.5 inches and that stress is the factor which brings more noise to the system.

The temperature was the variable with the greatest influence on results. It was observed that the lower the temperature, the lower the values for speed. One note on this analysis is that the stress, which is the main objective of the method, do not cause significant variation in the result. It is because of the level of stress chosen for our tests, which are below 10% of Yield Limit. So, our results show that our method is not sensible to changes in stress below 20 MPA, what is already expected. For future studies, higher differences will be used. We expect to have significant responses, as published by Andrino (2007). Another conclusion is that the influence factors have large influence on the results, more than the stress differences of 20 MPa. It results that we have to employ a very tight method of control of those factors during the process of measurement.

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9. RESPONSIBILITY NOTICE

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