DETERMINATION OF 5052 ALUMINUM ALLOY ACOUSTOELASTIC COEFFICIENTS

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Abstract. *The process of making parts using the 5052 aluminum alloys can use welding to joint different components or parts. Processes of welding normally introduce residual stresses in the welded components. One of the most promising methods to evaluate these residuals is the ultrasonic method. Several types of waves can be used with this method, but the most sensitive is the longitudinal critically refracted waves (Lcr). Acoustoelasticity is the study of the ultrasonic waves behavior, mainly their propagation speed, and the relation with mechanical stresses. The objective of this work is to analyze the relation between and the ultrasonic LCR wave speed. This relation is approximately linear and the angular coefficient of the best fit equation is called acoustoelastic coefficient (L11). Eight bars were assayed using a specially developed system controlled by a program called L- v.1.0. Four of them were taken with the major length aligned with the rolling direction and the remaining orthogonal to them. The tests were carried out in a tensile machine constructed for acoustoelastic coefficient evaluation in laboratory. The results showed low dispersion and significant differences in the results measured for both directions. With those coefficients, researches can develop future applications in the evaluation in field for parts made of 5052 aluminum alloys.*

Keywords: *ultrasonic evaluation, aluminum alloy, non-destructive evaluation, ultrasonic waves, L_{cr} Waves.*

1. Introduction

The non-destructive evaluation of the material properties has become more and more important in the project and life evaluation of components and systems. Residual stress, hardness and failure size must be taken into account in decisions on the need to repair or replace the items found in service. Residual stress and hardness are concern items only in new components, but also in old components in which the environment and time lead to changes in the properties that need to be monitored. Furthermore, homogeneity and direction variance in the properties are important parameters in the material selection for building critical components. There has been a significant progress in developing non-destructive techniques to determine these properties. If these techniques were used, it would be able to determine the material conditions in service, allowing the engineer not only to optimize the project, but also the maintenance cycle. Many present researchers discuss the possibilities and ways of using ultrasonic methods in measurements, texture studies, grain size determination and inspection of multiple layer materials for interface defects (Pão et al., 1991). They also discuss solutions to a great variety of experimental problems, analytical methodologies, computational mathematic problems, among others, involved in the use of ultrasonic methods.

Overall, the assessments aim to guarantee the use of material in proper conditions. In the non-destructive assessment area, the ultrasonic waves are traditionally used to detect, locate and analyze the discontinuity. Nowadays, a great number of other non-conventional uses of the ultrasonic waves have been developed, mainly in material and part characterization, for example, in the measurement of elasticity and modules. The use of ultrasonic techniques to determine is based on the wave speed variance, which occurs when these waves propagate through a material under stress. Such effect can be related to the stress state through the material elastic constants of third order. This phenomenon is called acoustic anisotropy (Lamy, et al., 2002).

The practical use of the ultrasonic technique involves the induction of longitudinal and transversal waves inside the material to be tested and in recording their time of flight. The wave speed inside materials obtained from the time of flight and distance, is a function of the interior stress state, as well as of other characteristics like texture, grain size, inclusions, etc. The speed variance magnitude depends on its propagation direction and on the particle movement direction (polarization) in the medium in relation to the material state and also to the crystalline plans. The phenomenon of wave speed variance with a state and the material elastic characteristics is called "acoustoelastic effect".

This paper aims to determine the values that relate to speed variance, called acoustoelastic constants, for aluminum 5052, using longitudinal critically refracted waves (L_{cr}). Eight bars were assayed, and half of them were cut in length (greater measurement) in the laminating direction, called longitudinal bars in this paper. The remaining bars were cut in the transversal laminating direction, called transversal bars. For a precise evaluation of the involved parameters, an evaluation of the material elasticity module was necessary for both laminating directions, using the pulse-echo method. The real acoustoelastic constants were experimentally determined using the correct values of the elasticity modules.

2. Theoretical review

The applied elasticity linear theory for small deformations is, in general, suitable for describing the material elastic behavior, leading to the elastic constants of second order, the Lamé constants, λ μ, to an isotropic material. However, the theoretical description of the acoustoelastic effect is only possible taking into account the non-linear theory of elasticity, which analyzes the finite deformations. Murnaghan included terms of third order when defining the elastic deformation energy and introduced the elastic constants of third order (*l, m, n*) for modeling the acoustoelastic problem, which were after called Murnaghan's constants. Based on his studies from 1951 and 1953, Hughes and Kelly developed the basic relations between ultrasonic wave speed and the deformation arising from the material where the wave propagated. They showed that a wave speed, when propagating in direction 1, the same direction of the applied force in an initially isotropic body submitted to a homogeneous tri-axial deformation field in a rectangular coordinate system, are shown by Eqs. (1), (2) and (3) (Lu, et al, 1996).

$$\rho_0 . V_{11}^2 = \lambda + 2\mu + (2l + \lambda).\theta + (4m + 4\lambda + 10\mu)\alpha_1 \tag{1}$$

$$\rho_0 . V_{12}^2 = \mu + (\lambda + m).\theta + 4\mu.\alpha_1 + 2\mu\alpha_2 - \frac{1}{2} n\alpha_3 \tag{2}$$

$$\rho_0 . V_{13}^2 = \mu + (\lambda + m).\theta + 4\mu.\alpha_1 + 2\mu\alpha_3 - \frac{1}{2} n\alpha_2 \tag{3}$$

In the previous equations, ρ_0 is the initial density and V_{11} is the longitudinal wave speed that propagates in direction 1, with the particles also moving in direction 1. V_{12} *and* V_{13} are the shear ultrasonic wave speeds that propagate in direction 1, with the particles moving in directions 2 and 3, respectively. λ and μ are elastic constants of second order, or Lamé's constants. Furthermore, *1, m* and *n* are elastic constants of third order named Murnaghan's constants, and α_1, α_2, α_3 are the main deformation components in directions 1, 2, 3. The total deformation is given by: $\theta = \alpha_1 + \alpha_2 + \alpha_3$.

In case of a uniaxial stress state, there are five wave propagation ways whose speeds can be determined by Eqs. (1) to (3). Taking into account the acting in direction 1, the deformations are: $\alpha_1 = \varepsilon$ and $\alpha_2 = \alpha_3 = -\nu\varepsilon$, where ν is the Poisson's coefficient. From these assumptions, Eqs. (1), (2) and (3) are reduced to the formula showed in Eq. (4) and (5) (Bray & Stanley, 1997).

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

$$\rho_0 . V_{12}^2 = \rho_0 . V_{13}^2 = \mu + \left[4\mu + \nu\left(\frac{n}{2}\right) + m(1 - 2\nu)\right]\varepsilon \tag{5}$$

The wave speed propagation in the perpendicular plan towards the uniaxial stress can also be determined by the following equations:

$$\rho_0.V_{22}^2 = \lambda + 2\mu + [2l(1-2\nu) - 4\nu(m + \lambda + 2\mu)]\varepsilon \quad (6)$$

$$\rho_0.V_{21}^2 = \rho_0.V_{31}^2 = \mu + \left[(\lambda + 2\mu + m)(1-2\nu) + \frac{n\nu}{2}\right]\varepsilon \quad (7)$$

$$\rho_0.V_{23}^2 = \rho_0.V_{32}^2 = \mu + \left[(\lambda + m)(1-2\nu) - 6\nu\mu - \frac{n}{2}\right]\varepsilon \quad (8)$$

In these equations, V_{22} is the longitudinal wave speed propagating in direction 1, with the solid particles vibrating in direction 2. V_{21} and V_{23} are the shear wave speeds that propagate in direction 2, with the solid particles vibrating in directions 1 and 3, respectively. From these equations, taking into account the relations between and deformation, it is possible to set the fundamental relations between ultrasonic wave propagation speed, both longitudinal and shear, and the stresses in the material.

We have the following equations for the parallel wave propagation towards the applied surface (Hughes, 1953; Lu, 1997):

$$\rho V_L^2 = \lambda + 2\mu + (\sigma/3K)[2l + \lambda + (\lambda + \mu)(4m + 4\lambda + 10\mu)/u] \quad (9)$$

$$\rho V_c^2 = \mu + (\sigma/3K)[m + (\lambda n/4\mu) + 4\lambda + 4\mu] \quad (10)$$

And the following equations for the perpendicular wave propagations towards the applied surface:

$$\rho V_L^2 = \lambda + 2\mu + (\sigma/3K)[2l - (2\lambda/\mu)(m + \lambda + 2\mu)] \quad (11)$$

$$\rho V_{c1}^2 = \mu + (\sigma/3K)[m + (\lambda n/4\mu) + \lambda + 2\mu] \quad (12)$$

$$\rho V_{c2}^2 = \mu + (\sigma/3K)[m - (\lambda + \mu) + n/2\mu - 2\lambda] \quad (13)$$

In the previous equations, σ is the uniaxial stress (positive for comprehensible and negative for traction); the subscribed c is the shear wave; the subscribed c_1 is the shear wave with parallel polarization towards stress; the subscribed c_2 is the shear wave with perpendicular polarization towards stress; the subscribed L is the longitudinal wave; ρ is the stress-free medium density and K is equal to $\lambda + 2\mu/3$.

The first factor in the left side of Eq. (9) and (13) describes the ultrasonic wave speed propagating in a stress-free body. In Eqs. (9) and (11), this factor is $\lambda + 2\mu$, and in Eqs. (10), (12) and (13) it is μ.

The equations developed by Hughes and Kelly can be joined to facilitate its practical use. They can be represented in terms of the ultrasonic wave speed variance in relation to stress, in general, as follows (Lu, 1996; Ortega, 2001; Schneider, 1997):

$$\frac{V_{ii} - V_l^0}{V_l^0} = k_1\sigma_i + k_2(\sigma_j + \sigma_k) \quad \text{(longitudinal waves)} \quad (14)$$

$$\frac{V_{ij} - V_c^0}{V_c^0} = k_3\sigma_i + k_4\sigma_j + k_5\sigma_k \quad \text{(shear waves)} \quad (15)$$

In the previous equations, V_l and V_c are the longitudinal and shear wave speeds in the material without stress respectively; V_{ij} is an ultrasonic wave speed propagating in direction i and polarized in direction j; σ_i, σ_j and σ_k are the main stresses in directions i, j *and* k; the coefficients k_1 *to* k_5 are called normalized acoustoelastic constants. Each acoustoelastic constant corresponds to a direction of the wave propagation and particle polarization, depending on the stress application direction, which are obtained from the wave speed relative variation of a mono-axial material, considering very small variances. These variances are obtained by the derivation of the applicable Eqs. (9 to 13) and from their division by the speed absolute values (Bittencourt, 2000).

Taking into account that there are requests only in direction 1, the second term in the right side of Eq. (14) is null. Using this equation when the waves are propagating in the same direction as the force application, we may obtain the following equation for determining the acoustoelastic constant L_{11} (Lu, 1996, Hughes, 1953, Bray, 2002):

$$d\sigma = \frac{E(dV_{11}/V_{11})}{L_{11}} = \frac{E}{L_{11}.t_o}dt \qquad (16)$$

In this equation, L_{11} is equal to ($k_1.E$). Using Eq. (15) with some mathematic skills, we may obtain the equation for determining the acoustic birefringence *B,* which depends on the acoustoelastic constant for transversal waves C_a (Lu, 1996).

$$B = B_0 + C_a\,(\sigma_1+\sigma_2) \qquad (17)$$

The birefringence shown in Eq. (16) is related to the propagation speed variance for waves with perpendicular polarization, according to Eq. (18).

$$B = 2\frac{(V_\theta - V_r)}{(V_\theta + V_r)} = -2\frac{(t_\theta - t_r)}{(t_\theta + t_r)} \qquad (18)$$

3. Equipments used

To evaluate the acoustoelastic constants, a mechanical system was developed, which applies known forces in the bars under testing. This system is basically a traction machine in which hydraulic cylinders allow the applied force in the bar to be calculated as a fit pressure function. Having the force and the bar area, it is possible to calculate the acting stresses.

The complete system to evaluate the acoustoelastic constants is shown in Fig. (1). Besides the traction machine (detail 1), the system has: the equipment for positioning and controlled pressure application between the set of ultrasonic sensors and the bar (detail 2); hydraulic pump for pressure application (detail 3); pulser-receiver - Parametrics 5073 PR (detail 4); Computer with a National Instruments NI 5911data acquisition board (detail 5).

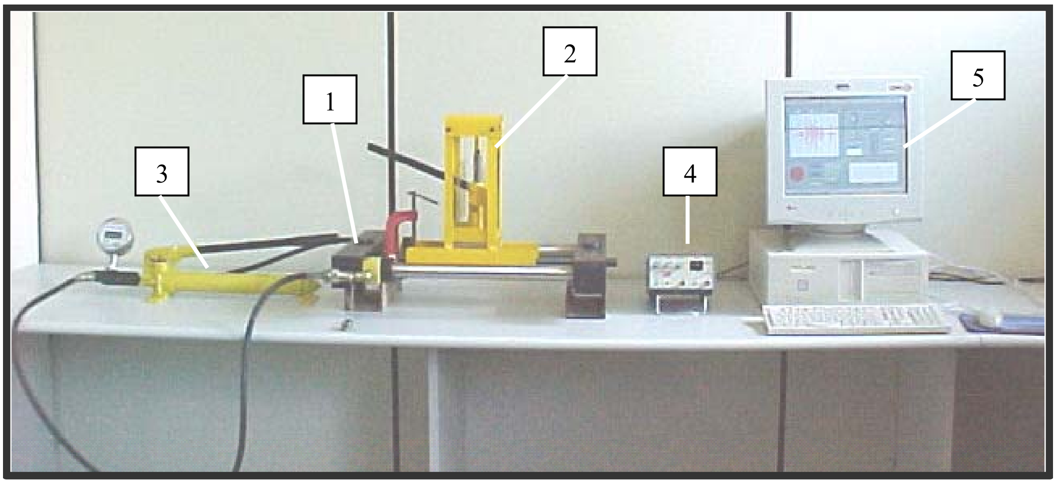


Figure 1: System for acoustoelastic constant determination

To generate and receive longitudinal waves, two transducers were set up in a base with two acrylic shoes, which allow the waves to hit and be picked up from the material surface in an angle of around 26º. The link between the shoes is made by an aluminum plate, which is used to apply the pressure needed to obtain the contact with the surface and keep the distance between the shoes fixed. This transducer display is necessary to excite the critically refracted waves or L_{cr} waves. The transducer setting can be seen in Fig. (2). The transducers in red, set up in the acrylic shoes, are by HARISONIC, their piezoelectric crystal measures 12,7 mm^2 and their natural frequency is 2,25 MHz.

To measure the times of flight, it was necessary that the pressure on the shoes with the transducers be controlled on the analyzed pieces. This pressure needs to be always the same as the setting shown in Fig. (2) is not infinitely hard and at any movement between the two transducers, even minimum, can lead to errors which could make the next analyses difficult. In order to understand better the importance of controlling the force, the value can be calculated in seconds for each additional millimeter of distance between the transducers. Taking into account the traversed distance by the wave in the acrylic of 1,3 cm, and traversal in the aluminum of 11,2 cm, and also using the speeds 2,8 x 10^5 cm\s and 6,3 x 10^5 cm/s, respectively for the acrylic and for the aluminum, we may obtain the values 357 ns/mm for the acrylic and 158,7 ns/mm for the aluminum. Considering that the sensibility is at an average 1,5 MPa/ns, it may lead to significant errors in stress measurements. To avoid this problem, a clamp was used to compress the setting against the piece surface. For the exact controlling of such force, a force cellule linked to a sign conditioner was used. It was fixed in one side of the clamp.

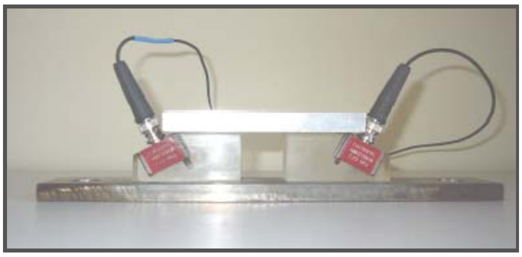


Figure 2: Probe for measuring stress based on ultrasonic waves (Miniccuci, 2003)

The program for data acquisition called L-Stress (Andrino, 2002) was developed to calculate stress in mechanical components through the time of flight measurement of the sub-superficial longitudinal waves (L_{cr} waves), using the acoustoelastic theory. The program was made in an instrumental developed platform LabVIEW. Using a data acquisition board, which simulates an oscilloscope, the program was able to pick up and measure the wave times of flight to a future calculation of stress and acoustoelastic constants.

4. Trial body description

To determine the acoustoelastic constant values and the elasticity module, a 5052 aluminum alloy plate was cut generating eight bars of size 760 x 70 x 9,525 mm. Four of them were cut with the greater length in the laminating direction and the other four were cut in transversal direction to laminating. The bars were numbered as 21, 22, 23 and 24 for the longitudinal bars, and as 11, 12, 13 and 14 for the transversal bars. The cut in the bars from the laminated plate was made using a regular metallic saw**,** to obtain the measures close to the mentioned above. After this process, the plates were tooling and faced in order to determine the final measurements. As the manufacturing process may lead to residual stresses, these bars were taken to a thermal treatment to alleviate stresses. Since the acoustoelastic constants must be measured from both sides of the bars, it was made a mark in each of them to avoid flexion effects and facilitate a future understanding of the results.

5. Procedure to determine the acoustoelastic constants and the elasticity modules

The basic procedure to evaluate stresses and future calculation of the acoustoelastic constants with the system is to progressively increase the force through the hydraulic system and measure the ultrasonic wave time of flight variance between the transducers. A maximum pressure of 150 kgf/cm^2 was chosen, which corresponds to the maximum applied in the bar by the hydraulic cylinders of 63,56 MPa. The pressure was divided into four steps and, for each one, an ultrasonic transducer was placed and taken out four times, always by cleaning it and placing a new coupling gel layer between the measurements. Figure (3) shows the force application system set to measure the time of flight. Detail 1 in the figure shows the positioner to control the ultrasonic transducer pressure, shown in detail 2, on the bar. Detail 3 shows the force application tractor on the bars.

After each trial and having the pressure value applied to the two pistons and their respective areas, it is possible to calculate the applied force in the bar. Having the force value applied to the bars, it is possible to calculate the real stress for each pressure stage. Having the track time value measured for each pressure step, the time of flight for the free-stage (without force application), the elasticity module value and the reference time, it is possible to calculate the numerical value of the product x acoustoelastic constant. The acoustoelastic constant value is the angular coefficient of the obtained graphic. The procedure was carried out for each bar mentioned in the item above. For each one, the acoustoelastic constant was determined for each side; the final acoustoelastic constant for each bar individually is the means of the results for both sides.

To determine the bar elasticity modules, the ultrasonic method used was the pulse-echo one. In it, an only transducer is responsible for emitting and receiving the ultrasonic signs. The equipment used is the same one for the acoustoelastic constant determination. However, for this determination, the bars were not necessary to be taken to traction, eliminating the need for an actuator.

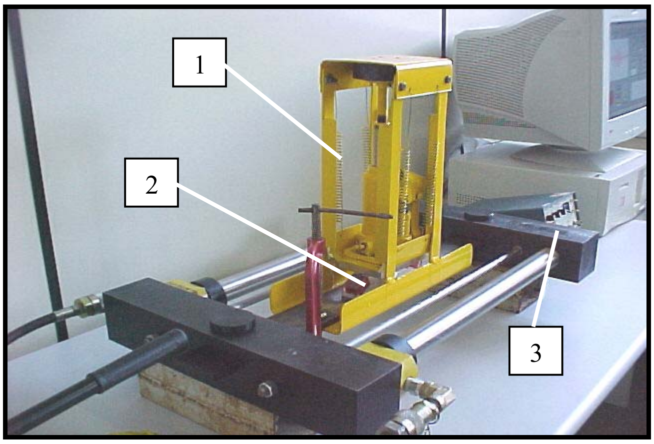


Figure 3: Trial body traction machine for determining the acoustoelastic constants

To determine the elasticity module, 3 bars were used in each lamination direction. The bars are: 11, 12, 13, 21, 22, 23. Having those bars, the ultrasonic transducers generating the longitudinal and transversal waves were used for determining the time of flight. Each bar was measured in three positions. In each measurement point, the both transducers were placed and taken out three times. For each point, a mean was made and the respective standard deviation was calculated. A new mean was made with the previous means to determine the final time of flight used to calculate the elasticity module. Through specific equations that have transversal and longitudinal ultrasonic wave speeds, it is possible to calculate the module value for each bar (GE Panametrics, 2003; Caetano et al., 2005).

6. Experimental Results

Table 1 shows the results obtained for the 5052 aluminum elasticity modules, using transversal and longitudinal ultrasonic waves (Caetano et. al. , 2005).

Table 1: Elasticity modules calculated with the ultrasonic method

Plates	11	12	13	Average	Deviation
Elasticity module (MPa)	67797.0	67850.1	67826.2	67824.5	26,63
Plates	21	22	23	Average	Deviation
Elasticity module (MPa)	68818.6	68336.5	69052.9	68736.0	365,3

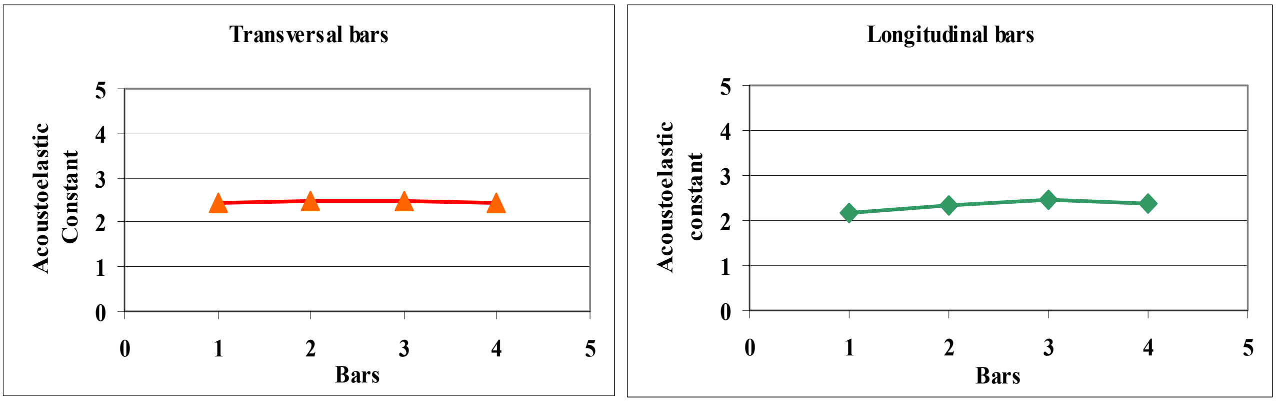
In this table, we may observe a small dispersion between the module values for each bar set, for each lamination direction. The standard deviation for both directions was less than 1% of the value found for the studied direction. The results also showed that the elasticity module values for the plates were close, with a difference of 1,3%. We may conclude that for 5052 aluminum case, the lamination direction does not have a significant influence on the elasticity module value. It is only necessary to know its correct value.

Using the equipment described above, each plate was measured and the corresponding acoustoelastic constant was determined. Basing on one side of the longitudinal bar 22, a small dispersion was verified between the measurement points. The greater standard deviation was 2,5 ns, which means a sensibility of 1,5 MPa/ns, and when this aluminum is together with the used measurement system, a value of 3,75 MPa. This value means a great solution for non-destructive trials in Mechanical Engineering. Table 2 shows the results found for all the bars, for each side and the respective average.

Table 2: Acoustoelastic constant values (5052 Aluminum)

Bars	11	12	13	14	21	22	23	24
Superior side	2,49	2,41	2,35	2,77	2,25	2,42	2,41	2,31
Inferior side	2,37	2,55	2,65	2,14	2,11	2,28	2,47	2,47
Side average	2,43	2,48	2,50	2,45	2,18	2,35	2,44	2,39

Figures 4a and 4b show all the acoustoelastic constant values calculated for the bars. Each constant was calculated for each bar side and after a value average was made. Each constant final value was obtained by the average of the four bars for each lamination direction.



(a) (b)

Figure 4: 5052 Aluminum acoustoelastic constants: a) Transversal bars; b) Longitudinal bars

In general, we may observe from the figures that the transversal bars presented greater magnitudes for the constants than the longitudinal bars. This fact confirms other papers relating to the acoustoelastic constant determination (Caetano, 2003, Andrino, 2003), with other kinds of metallic materials. The constant average values for the longitudinal bars, that were already corrected due to the elasticity module, was 2,34, and for the transversal bars, 2,46. Table 3 shows the constant values for the longitudinal and for the transversal bars with the respective standard deviation.

Table 3: Acoustoelastic constants for the bar sets

Acoustoelastic constants	
Longitudinal bars	**Transversal bars**
2,18	**2,43**
2,35	**2,49**
2,44	**2,50**
2,39	**2,45**
Average	**Average**
2,34	**2,46**
Standard deviation	**Standard deviation**
0,11	**0,03**

7. Conclusion

This paper showed that the acoustoelastic method can be used to estimate stresses in mechanical elements. It was verified a small dispersion between the measured values, proving that the ultrasonic system used is efficient and trustful for this kind of determination.

In the experiments, the bar acoustoelastic constants were calculated. With these constants, it is possible to calculate the material stressed, both the applied and the residual ones. Having these results, it is also possible to evaluate the component conditions made with aluminum plates when they are working and verify their tendency to failure.

Nowadays, this method represents the state of art in measuring stress and it has been developed in several universities and international institutes. Studied have been done to develop applications and create new forms of generating and receiving waves, as well as controlling the influence variable effect. The results of this paper may allow the stress state evaluation in many real situations. The next step is the application of the obtained values in evaluating the stresses due to welding in aluminum structures and the study of relaxation found in the components due to the welding.

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