Acoustoelastic Coefficients for Commercially Produced 6XXX and 7XXX Series Aerospace Aluminum Plate

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Abstract

Laboratory experiments are reported on the acoustoelastic behavior of aluminum aerospace plate. Acoustoelastic constants are essential for application of the L_{CR} technique for nondestructively measuring stresses in aluminum plate and parts manufactured there from. This work reports on the results obtained from three commercially produced aluminum alloy plates. These results are compared to recent results obtained by other researchers for similar wrought aluminum products. Suggestions for future work to enhance the application of ultrasonic methods for measuring residual stress are given.

Introduction

The aerospace industry uses many monolithic parts machined from aluminum plate. A key issue for the cost-effectiveness of this process is to minimize distortion after machining. Excessive machining distortion may result in the need for costly and time consuming re-work prior to installation of the component on the aircraft. In severe machining distortion cases the parts are scrapped. To solve this problem a manufacturing process must be developed that is capable of providing aluminum plates that meet all of the mechanical properties requirements in combination with consistently lower residual stress levels. Machining distortion can be directly related to the strain energy density of a plate. Prime and Hill [1] and Schultz and Karabin [2] have discussed this relationship and the fact that strain energy density, *e*, can also be directly related to the residual stress range, Δσ, of a plate. Equation (1) below defines strain energy density, or stored elastic energy per unit volume. Equation (2) describes the relationship between machining distortion, strain energy density and residual stress range of a plate (which can be measured).

$$e = \frac{1}{t}\int_0^{1/2} \frac{\sigma(z)^2}{E}\, dz \tag{1}$$

$$Machining\ Distortion = e^{1/2} = \Delta\sigma \tag{2}$$

where *t* the thickness of the plate, *E* is the elastic modulus and *z* is the through thickness position. Figure 1 is a plot of the through thickness residual stress profile of a stretched and artificially aged 7175-T7351 50 mm plate with a residual stress range of 13 MPa [3].

There are a variety of destructive test methods available to plate manufacturers. Unfortunately, many of these methods are costly and time-consuming due to the fact that they consume portions of the plate. There is a need, therefore, to develop a robust, cost effective non-destructive residual stress measurement system that delivers repeatable results and is suitable for use in a large-scale manufacturing environment.

Ultrasonic, non-destructive investigations of residual stresses in engineering materials has seen rising interest in recent years because of the convenience of the nondestructive technique and the resulting fact that a large number of measurements can be collected from a particular sample. The large number of measurements gives a better sampling of stress distributions in a part. A primary limitation of the ultrasonic technique thus far has been the scarcity of acoustoelastic coefficients relating the velocities (or travel-time) measured and the actual stress in the material.

Over the last 30 years the L_{CR} ultrasonic technique has been developed into an effective method for nondestructively evaluating surface and near surface material properties [4]. Application of the L_{CR} technique to stress measurement has evolved into a procedure that can fulfill the previously stated requirements. In comparison to other ultrasonic waveforms, it is most sensitive to stress change and least sensitive to material texture. Moreover, changing the frequency, which enables the evaluation of stress gradients, may vary the penetrating depth. Bray, Kim and Fernandes demonstrated this capability in commercially produced aluminum plate where they were able to distinguish between various tempers and residual stress levels [5]. That work used an earlier version of the test method and equipment than was used in this paper.

The characteristics of the L_{CR} technique are where an incident (T) wave at approximately the first critical angle (Θ), determined by Snell’s Law, excites a bulk, longitudinal (L_{CR}) wave in the material [6]. It is received by dual receivers R_1 and R_2, separated by a distance, d. The stress variation ($\Delta\sigma_1$) with measured velocity change can be written in terms of Young's modulus (E) and the acoustoelastic coefficient (L_{11}) (Equation 3). Velocity change is measured using the two L_{CR} receiving transducers. Where the distance between longitudinal ultrasonic transducers is kept the same for all measurements, the velocity can be replaced by the travel time. Equation (3) shows the resulting equation where t_o is the reference time-of-flight for an unstressed state and Figure 2 is a schematic diagram of dual receiver L_{CR} probe set-up.

$$\Delta\sigma_1 = \frac{E\left(dV_{11}/V_{11}\right)}{L_{11}} = \frac{E}{L_{11} \times t_0} dt \qquad (3)$$

Plate rolling produces through thickness texture gradients (preferred crystallographic orientations) that significantly affect ultrasonic wave speeds. As a result it is important to understand the acoustoelastic properties of the thickness layer being inspected for both the rolling direction (longitudinal (L)) and the transverse direction (long-transverse (LT)).

An acoustoelastic coefficient (L_{ij}) is required to relate the measured travel-time and the stress. For the L_{CR} wave i = j = 1 where the direction of wave propagation and the particle motion are parallel to the surface and Equation 3 may be rearranged as shown in Equation 4.

$$L_{11} = E(\Delta V / V) / \Delta\sigma_1 \qquad (4)$$

where E is the elastic modulus, ΔV is the measured change in velocity, V is the velocity in a reference state and $\Delta\sigma_1$ is the change in stress.

Equation (4) can be simplified further and represented as:

$$K_{11} = (\Delta V / V) / \Delta\sigma_1 \qquad (5)$$

where the elastic modulus is now incorporated in the constant, K_{11}.

The present paper describes the test method used to establish the acoustoelastic coefficients for three commercially produced wrought aluminum plates: (1.) 6061-T651, (2.) 7050-T7451 and (3.) 7175-T7351.

In recent years, several investigators have conducted experiments focused on determining acoustoelastic constants for aluminum wrought products. Most notable amongst these papers are Andrino et al (AA 5052) [7], Tanala (5086) [8], Ya, et al. (AA 6056) [9], and Gachi (AA7108) [10]. The results of these researchers are compared against the results from this study.

Experimental Setup

Samples

Three commercially produced aluminum plates were studied as a part of this work: (1.) 6061-T651 general engineering tooling and jig plate, (2.) 7050-T7451 aerospace structural plate and (3.) 7175-T7351 aerospace structural plate. All of these plates were hot rolled to 13 mm, solution heat treated, stretched and artificially aged in accordance with the Aerospace Material Specification (AMS) for wrought processing of aluminum raw materials (AMS 2772) [11]. Each of the plates studied meets all of the applicable AMS material property requirements for the particular plate alloy, temper and thickness. Table 1 summarizes chemical composition of each of these plates. Table 2 summarizes the static properties in both the longitudinal and long-transverse directions.

Table 1 Chemical compositions of the three aluminum plates used in this study

CHEMICAL COMPOSITION										
ALLOY	**TEMPER**	**THICK**	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Zr**
7175	T7351	13 mm	0.06	0.14	1.43	0.010	2.47	0.212	5.64	
7050	T7451	13 mm	0.05	0.08	2.21	0.008	2.19	0.003	6.11	0.09
6061	T651	13 mm	0.73	0.56	0.34	0.062	1.04	0.206	0.12	

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Longitudinal (L) and long-transverse (LT) residual stress sample pairs were sectioned from each of the plates described above. The residual stress samples were 63 mm wide, by 813 mm by full plate thickness (13 mm). Figure 3 is a diagram of the residual stress samples extracted from these plates.

Table 2 Summary of the static material properties for the aluminum plates studied.

STATIC PROPERTIES

ALLOY	TEMPER	THICK	Longitudinal			Long-Transverse		
			YTS (MPa)	UTS (MPa)	Elong (%)	YTS (MPa)	UTS (MPa)	Elong (%)
7175	T7351	13 mm	467.8	534.7	15.2	468.9	536.1	14.7
7050	T7451	13 mm	503.7	553.3	14.9	501.6	554.0	13.9
6061	T651	13 mm				305.1	336.8	16.1

Load Frame and Stress/Strain Instrumentation

The bars cut from the plates were loaded into the tensioning frame as shown in Figure 4. The rigid bars of the tension frame on each end were fitted with hydraulic pistons each capable of 44.5 N (10,000 lb) force. Strain gauges were applied to the top and bottom surfaces of the samples described in Figure 3. The strain measured from each of these gauges was monitored as the load was incrementally increased. A typical stress-strain measurement sequence involved five or six steps where the stress was varied from 0 psi to 82.7 MPa (12,000 psi). The same tensioning frame used in this study was also use during a previous study for steel samples as reported by Santos and Bray [12].

Ultrasonic travel times were collected on the top of the bar with the patented L_{CR} probe shown in Figure 5 and L_{CR}StressMap^{TM} software on the PC shown at the rear. Pressure application necessary to obtain accurate readings was accomplished with the U-frame shown on top of the probe.

Results

Velocity-stress results are shown in Figure 6 for a 13 mm 6061-T651 sample oriented longitudinally (i.e. in the rolling direction). Stress was measured by the top strain gauge. In the data set, there were points where the piston stress indicated a change in load and no change occurred in the strain gauge reading. It was felt that these data could be affected by experimental error such as alignment of the tension frame and as a result these points have been omitted from this analysis.

Figure 7 shows similar results for a 13 mm 7050-T7451 plate sample oriented longitudinally and Figure 8 shows data for 13 mm 7175-T7351 plate samples oriented in the longitudinal (a.) and long-transverse (b.) directions, respectively.

Discussion

The results shown in Table 3 show strong trends and good correlation, even with the small number of data points for 7175 LT. This is due to the very strong acoustoelastic effect in these materials.

Table 3 Acoustoelastic results for the longitudinal (L) and long-transverse (LT) aluminum plate samples (where n represents the number of measurements).

Sample	**L_{11}**	**n**	**R^2**
6061 L A	3.39	6	0.90
7050 L A	2.90	8	0.95
7175 L A	2.87	8	0.94
7175 LT A	2.93	4	0.93

These experimental results compare favorably with previously cited results obtained by other researchers using various aluminum grades, as shown in Table 4. Notably, the acoustoelastic coefficients for 6061 and 6056 in the two data sets agree well, and the acoustoelastic coefficient for the 7175 grade aluminum is close to that of the 5052 and 5086 results reported in Table 4.

From Table 4, the acousto-elastic results for 7108 do not compare well against the 7175 data developed during this study. This is not surprising, due to the fact that 7108 is a Zr containing alloy as compared to 7175 which is a Cr containing alloy. As a result, the grain structures of these two alloys develop differently during thermomechanical processing. Since 7108 is a Zr containing alloy it compares more favorably with 7050, which is also a Zr containing alloy. The 7050 acousto-elastic constants are 3.22 for L and 3.3 for LT, which are closer to the 3.77 numbers shown in Table 4.

Table 4 Acoustoelastic coefficients reported by other researchers.

	5052 Andino et al. [7]	5086 Tanala, et al [8]	6056 Ya, et al [9]	7108-T79 Gachi [10])
L_{11} longitudinal	2.34	2.7		
L_{11} transverse	2.46	3.1		
K_{11}			$5.04x(10)^{-5}$ MPa	$4.97(10)^{-5}$ MPa
L_{11}			3.83	3.777

Note –Ya and Gachi reported results at K_{11}. The value for L_{11} is calculated using $E=72(10)^3$ MPa

To further explain potential differences between the results of the different researchers in Table 4 it would be necessary to fully characterize the microstructural differences between the various samples. As described earlier it is well understood that slight differences in grain morphology, recrystallization fraction and texture can significantly impact L_{CR} wave speed. The plates used during this study are essentially unrecrystallized with a very strong rolling texture near the surface where the L_{CR} wave speeds were measured.

Future Work:

Several additional tasks need to be accomplished in order to derive full benefit of the L_{CR} technique for stress evaluation, primarily developing experience in application. These tasks are outlined below:

1. Perform laboratory experiments to establish acoustoelastic coefficients (L_{11}) for a variety of materials.
2. Establish test standardization blocks so that different applications of the technique could be demonstrated to show uniform performance.
3. Evaluate the ability of different frequencies to characterize stresses at depths.
4. Integrate ultrasonic stress measurement into the engineering thought process so that design and manufacturing can be optimized.
5. Develop test systems which will collect travel-time data in an efficient manner.

Summary

Acoustoelastic coefficients were shown to vary by as much as 20% between commercially produced 6061, 7175 and 7050 plates, which highlights the importance of using the correct acoustoelastic coefficients for the material being studied. Making acoustoelastic data more readily available to researchers will encourage new applications of the L_{CR} method improving the overall quality of ultrasonic stress measurements. Good acoustoelastic data coupled with an L_{CR} probe set-up capable of measuring very small changes in travel-time are critical to making good stress measurements in wrought aluminum materials. The equipment described in this paper is capable of measuring travel-time with a resolution of 3-5 ηs in aluminum, which is equivalent to a stress resolution of +/- 1.7 MPa (+/- 0.25 ksi) for AA7050.

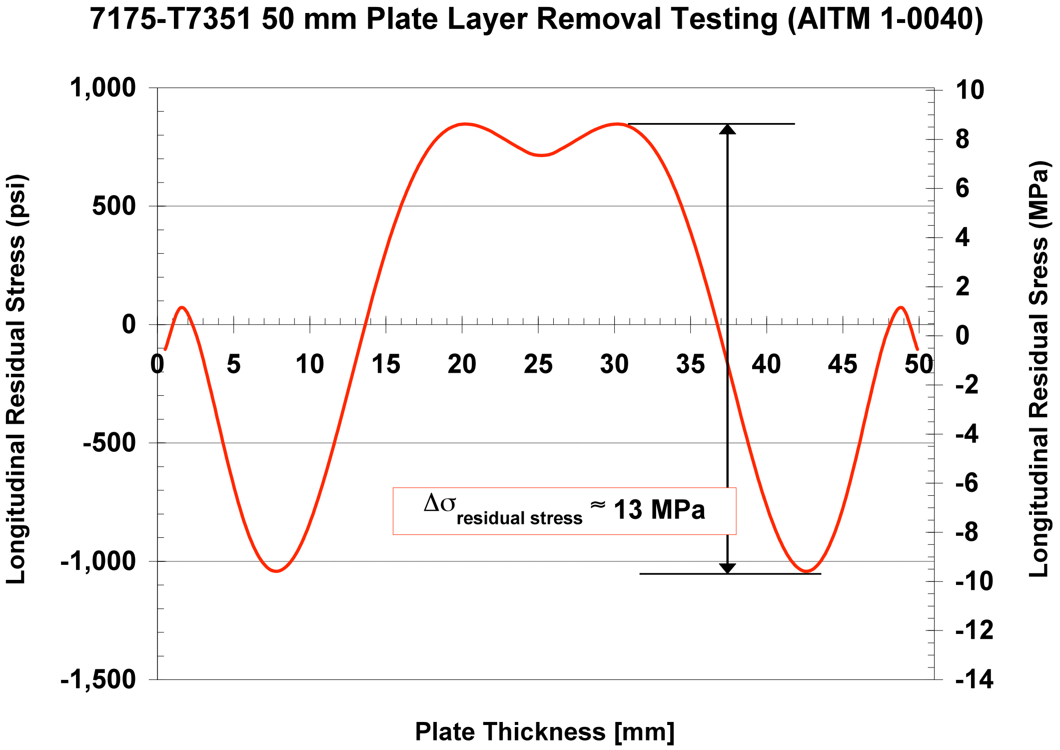

Figure 1 Through thickness residual stress profile of a 50 mm 7175-T7351 plate measured using the Airbus layer removal method (Airbus Industrie, 2001).

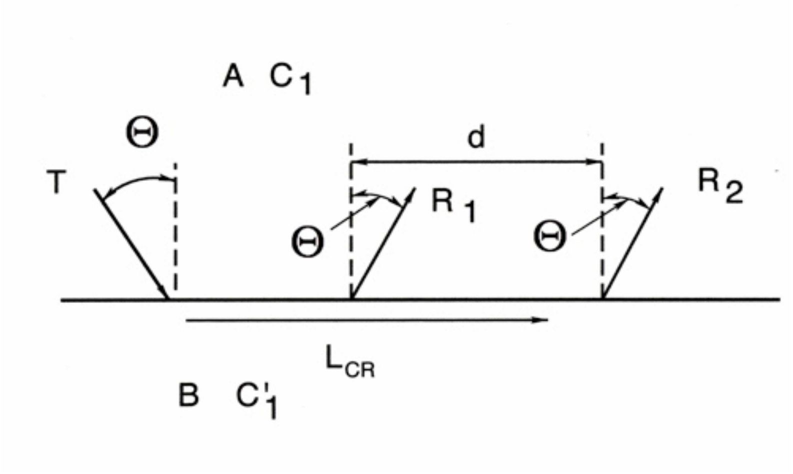

Figure 2: Schematic diagram of a dual receiver L_{CR} probe.

Figure 3: Dimensional drawing of the residual stress samples (tensile bars) used to generate the acoustoelastic coefficients for the plates studied (dimensions are in millimeter)

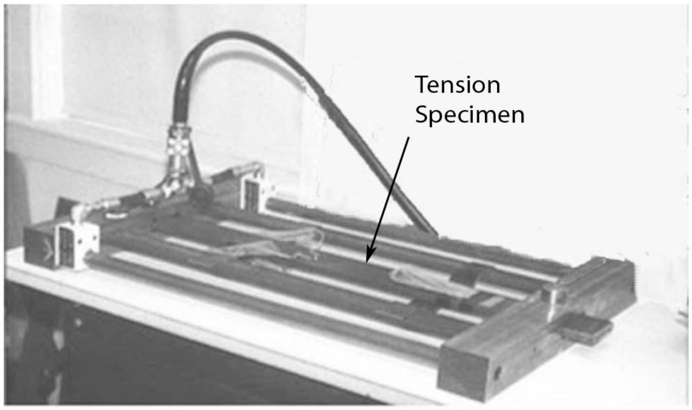

Figure 4: Tension frame used to load the plate samples in tension.

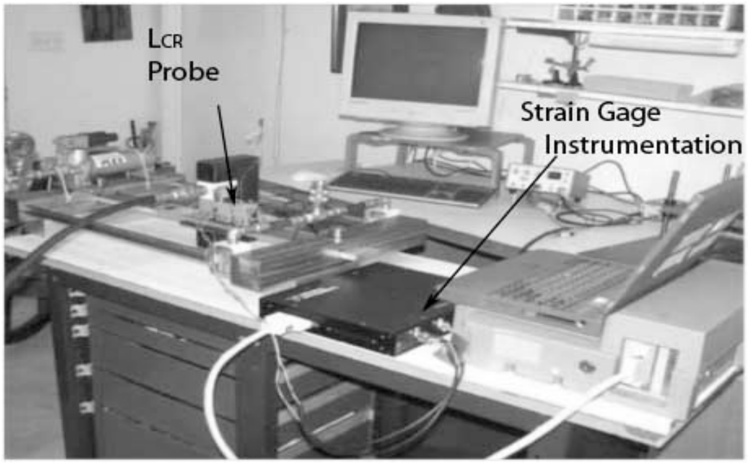

Figure 5: Experimental setup showing tension frame with L_{CR} probe (at left), strain gauge apparatus (at right) and ultrasonic setup at rear.

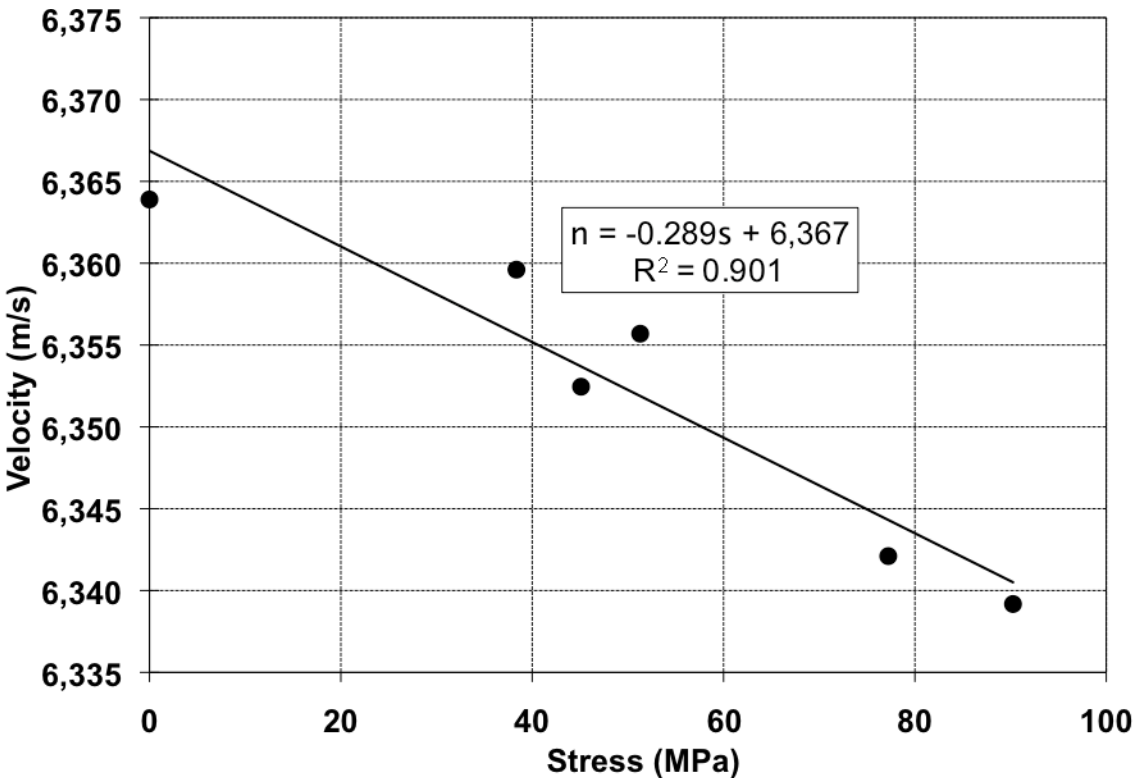

Figure 6 Velocity-stress relationship for 6061 longitudinal sample.

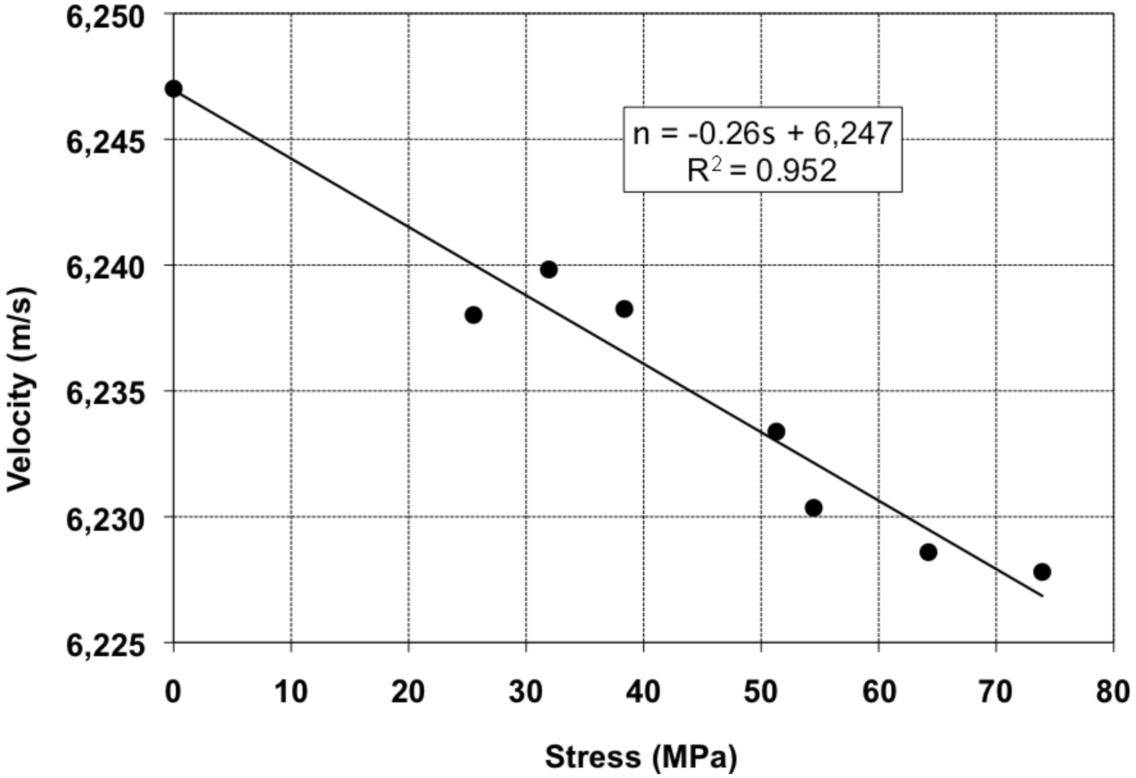

Figure 7 Velocity-stress relationship for 7050 sample oriented longitudinally.

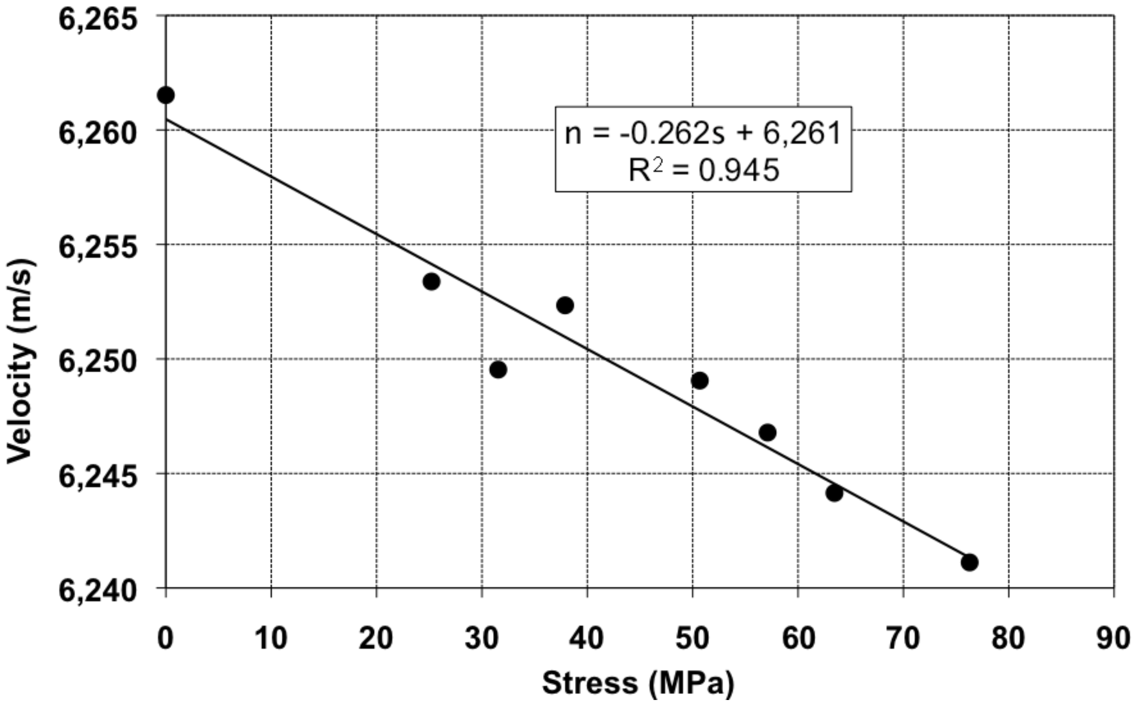

Figure 8 (a) Velocity-stress relationship for 7175 bar oriented longitudinally

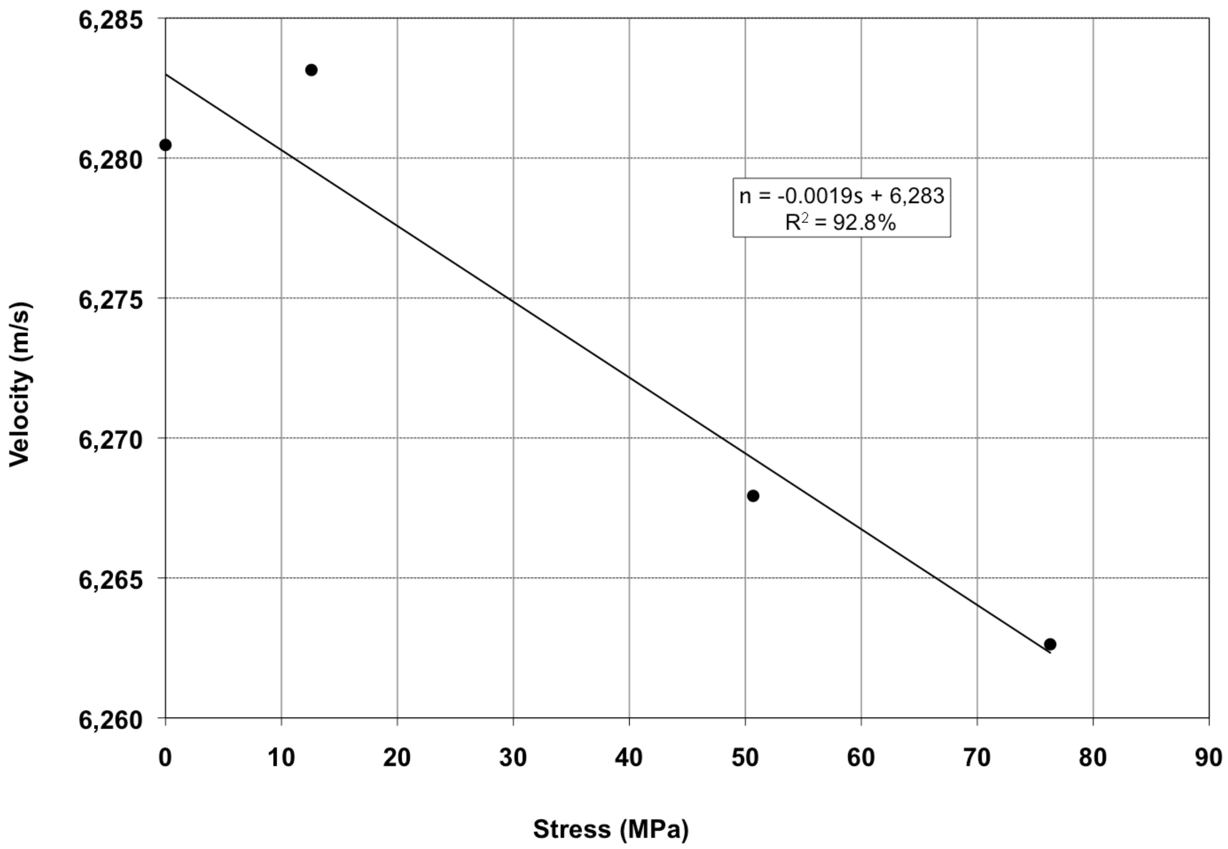

Figure 8 (b) Velocity relationship for 7175 bar oriented in the long-transverse direction (perpendicular to the rolling direction).

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