Hindawi Publishing Corporation
Advances in Materials Science and Engineering
Volume 2013, Article ID 746187, 8 pages
http://dx.doi.org/10.1155/2013/746187

Research Article

Employing the L_{CR} Waves to Measure Longitudinal Residual Stresses in Different Depths of a Stainless Steel Welded Plate

Yashar Javadi[1] and Sergej Hloch[2]

[1] *Department of Mechanical Engineering, Semnan Branch, Islamic Azad University, Semnan 35131-37111, Iran*
[2] *Faculty of Manufacturing Technologies, Technical University of Košice with a Seat in Prešov, Bayerova 1, 080 01 Prešov, Slovakia*

Correspondence should be addressed to Sergej Hloch; hloch.sergej@gmail.com

Received 23 February 2013; Accepted 9 July 2013

Academic Editor: S. Miyazaki

Ultrasonic stress measurement is based on the acoustoelasticity law which presents the relationship between the stress and acoustic wave velocity in engineering materials. The technique uses longitudinal critically refracted (L_{CR}) waves that travel parallel to the material surface. The L_{CR} wave is a bulk longitudinal wave that propagates within an effective depth underneath the surface while the penetration depth of a L_{CR} wave depends on its frequency. It is possible to measure the residual stress in different depths by employing different frequencies of the L_{CR} waves. This paper evaluates welding residual stresses in different depths of a plate made of austenitic stainless steel (304L). The penetration depths are accurately measured for the L_{CR} waves produced by 1 MHz, 2 MHz, 4 MHz, and 5 MHz transducers. Residual stresses through the thickness of the plate are then evaluated by employing four different series of transducers. It has been concluded that the L_{CR} method is nondestructive, easy and fast, portable, readily available, and low cost and bulk measuring technique which can be accurately employed in through-thickness stress measurement of austenitic stainless steels.

1. Introduction

Residual stresses are available in materials without any external force, and normally result of deformation heterogeneities appearing in the equipment. They have very important role in the strength and service life of structures. Welding is an assembly process often used in different industries, especially in the pressure vessel industry [1]. According to the process and temperatures reached during this operation, dangerous thermomechanical stresses may appear in and around the welded joint. To achieve a proper design of structure and control their mechanical strength in service, it is very important to determine the residual stress levels with a nondestructive method. Rising industry demand for the stress measurement techniques encouraged development of several methods like X-ray diffraction, incremental hole drilling, and the ultrasonic methods. Many studies showed that there is no universal or absolute method that gives complete satisfaction in the nondestructive stress monitoring of the mechanical components. Many parameters such as material, geometry, surface quality, cost, and accuracy of the measurement must be taken into account in choosing an adequate technique.

The ultrasonic technique was selected for stress measurement because it is nondestructive, easy to use, and relatively inexpensive. However, it is slightly sensitive to the microstructure effects (grains size [2–4], carbon rate [5, 6], texture [7–10], and structure [11–13]) and to the operating conditions (temperature [14, 15], coupling [16, 17], etc.). The ultrasonic estimation of the residual stresses requires separation between the microstructure and the acoustoelastic effects.

2. Theoretical Background

Within the elastic limit, the ultrasonic stress evaluating technique relies on a linear relationship between the stress and the travel time change, that is, the acoustoelastic effect [18, 19]. The L_{CR} technique uses a special longitudinal bulk

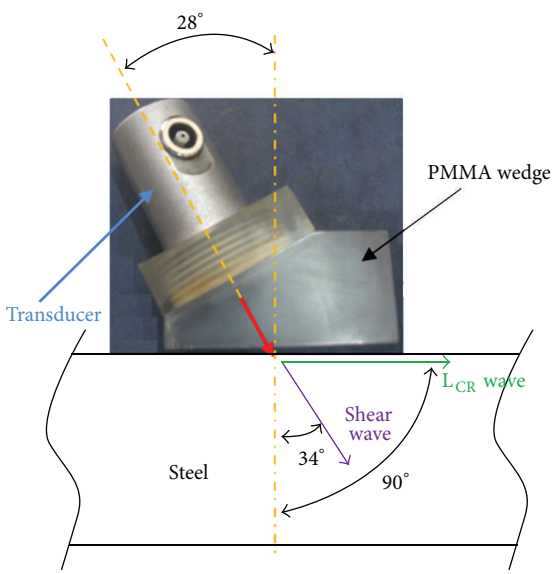


Figure 1: L_{CR} probe for PMMA (Plexiglas) wedge on steel.

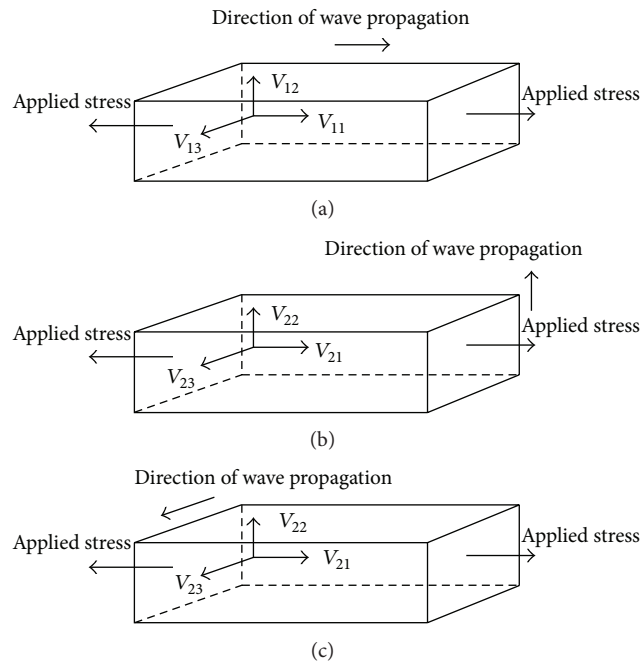


Figure 2: Velocity of plane wave and stress field in orthogonal directions [33].

wave mode, as shown in Figure 1, which travels parallel to the surface, particularly propagating beneath the surface at a certain depth. The L_{CR} waves are also called surface skimming longitudinal waves (SSLW) by some of the authors. Brekhovskii [20], Basatskaya and Ermolov [21], Junghans and Bray [22], and Langenberg et al. [23] had some detailed discussions on the characteristics of the L_{CR}. The capabilities of the L_{CR} waves in stress measurement of stainless steels are recently confirmed in different publications [24–32].

Ultrasonic stress measurement techniques are based on the relationship of wave speed in different directions with stress. Figure 2 shows elements of a bar under tension where the ultrasonic wave propagates in three perpendicular directions.

The first index in the velocities represents the propagation direction for the ultrasonic wave and the second represents the direction of the movement of the particles. In Figure 2(a), the wave propagates parallel to the load and V_{11} represents the velocity of the particles in the same direction (longitudinal wave), meanwhile V_{12} and V_{13} represent the velocity in a perpendicular plane (shear waves).

In Figures 2(b) and 2(c) the waves propagating in the other directions and the velocities are shown. The V_{22} velocity is for longitudinal waves propagating perpendicular to the stress direction. The sensitivity of these waves to the strain has been established by Egle and Bray [18] in tensile and compressive load tests for a bar of rail steel. The waves with particle motion in the direction of the stress fields showed the greatest sensitivity to stress, and those with particle motions perpendicular to the stress field showed the least. The most considerable variation in travel time with the strain was found for longitudinal waves, followed by the shear waves when the particles vibrate in the direction of the load. The other waves do not show significant sensitivity to the strain. The velocities of the longitudinal plane waves traveling parallel to load can be related to the strain (α) by the following expressions:

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

where ρ_0 is the initial density; V_{11} is the velocity of waves in the direction 1 with particle displacement in the direction 1; λ, μ are the second order elastic constants (Lame's constants); l, m, n are the third order elastic constants; $\theta = \alpha_1 + \alpha_2 + \alpha_3$, where α_1, α_2, and α_3 are components of the homogeneous triaxial principal strains. For a state of uniaxial stress, $\alpha_1 = \varepsilon$, $\alpha_2 = \alpha_3 = -\upsilon \times \varepsilon$, where ε is the strain in direction 1 and υ is Poisson's ratio. Using these values, (1) becomes

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

The relative sensitivity is the variation of the velocity with the strain and can be calculated by (3). In this equation, L_{11} is the dimensionless acoustoelastic constant for L_{CR} waves:

$$\frac{dV_{11}/V_{11}}{d\varepsilon} = 2 + \frac{(\mu + 2m) + V\mu\,(1 + 2l/\lambda)}{\lambda + 2\mu} = L_{11}. \quad (3)$$

The values of acoustoelastic constants for the other directions can be obtained in the same way. The variation in the V_{11} velocity, controlled by the coefficient L_{11}, is much greater than the other ones, indicating that these waves are the best candidates to be used in the stress evaluation. Stress can be calculated by the one-dimensional application of

the stress-strain relations in elastic solids. Equation (3) can be rearranged to give the stress variation in terms of time of flight (dt/t_0), as shown in (4), where t_0 is the time for the wave to go through a stress-free path in the material being investigated:

$$d\sigma = \frac{E\left(dV_{11}/V_{11}\right)}{L_{11}} = \frac{E}{L_{11}t_0}dt. \quad (4)$$

In (4) $d\sigma$ is the stress variation (MPa) and E is the elasticity modulus (MPa). The same equation can be used for the other directions of the waves, provided the value of the acoustoelastic coefficient L is changed. For a fixed probe distance, the travel time of the longitudinal wave decreases in a compressive stress field and increases in a tensile field. The acoustoelastic constant (L) functionally links the stress and the velocity or travel time change.

3. Experimental Procedures

3.1. Sample Description. The materials tested (A240-TP304L) are commonly used in pressure vessel industries. Single pass butt-weld joint geometry with a back-weld pass and without root gap is used. Two 600 × 250 × 10 mm normalized rolled plates are welded in V-groove (90° included angle). The back-weld pass and the main-weld pass are performed by the submerged arc welding (SAW) process (Figure 3).

3.2. Measurement Devices. The measurement device, shown in Figure 4, includes an ultrasonic box with integrated pulser and receiver, computer, and three normal transducers assembled on an integrated wedge. A three-probe arrangement is used, with one sender and two receivers in order to eliminate environment temperature effect to the travel time. Twelve transducers with four different frequencies are used where their nominal frequencies are 1 MHz, 2 MHz, 4 MHz, and 5 MHz. Using different frequencies helps to evaluate residual stresses through the thickness of the plates. The diameter of all the piezoelectric elements is 6 mm. The transducers are assembled on an integrated PMMA wedge. The ultrasonic box is a 100 MHz ultrasonic testing device which has synchronization between the pulser signal and the internal clock, which controls the A/D converter. This allows very precise measurements of the time of flight—better than 1 ns.

3.3. Determination of L_{CR} Depth. When the L_{CR} technique is applied to an application with limited wall thickness, the depth of the L_{CR} wave penetration is expected to be a function of frequency, with the low frequencies penetrating deeper than the high frequencies. There is no reliable equation for the relation of L_{CR} depth and frequency, hence, it should be measured experimentally. Four different frequencies have been used in this work to evaluate the residual stress through the thickness of the plates. Therefore, the penetration depths related to all of four frequencies should be exactly measured. The setup shown in Figure 5 is used to measure depth of the L_{CR} waves. Two transducers as sender and receiver with the same frequency are employed to produce the L_{CR} wave. A slot is cut between the transducers by employing a milling tool to prevent the L_{CR} wave from reaching the sender transducer. The depth of slot is increased step by step while amplitude of the L_{CR} wave is measured in each step. When amplitude of the L_{CR} wave is equal to the noise, the milling process is stopped. As a result, the depth of slot represents depth of the L_{CR} waves for the tested frequency. The material used here is the same as the welded plate material. The results of these measurements are shown in Table 1. It has been concluded that depths of the L_{CR} wave are equal to 5 mm, 2 mm, 1.5 mm, and 1 mm for transducer with nominal frequencies of 1 MHz, 2 MHz, 4 MHz, and 5 MHz, respectively.

3.4. Evaluation of the Acoustoelastic Constants. To evaluate the calibration constants (acoustoelastic constant, free stress time of flight), the calibration samples are taken from both sides of the plates. Two rectangular tension test specimens are extracted to determine acoustoelastic constant (L_{11}) by averaging the results. To evaluate the residual stress from (4), the value t_0 is measured directly from the stress-free samples and the acoustoelastic constant is deduced experimentally from a uniaxial tensile test associated with an ultrasonic measurement (Figures 6 and 7). In Figure 7, K represents the slope of the relative variation curve of the time of flight as described by

$$K = -\frac{\left(t - t_0\right)}{\sigma \times t_0}. \quad (5)$$

In (5), σ is the applied stress; t and t_0 are the time of flight measured between the two receivers for stressed and unstressed samples, respectively. The acoustoelastic constant (L_{11}) is equal to ($-K \times E$), where K is calculated from (5) and E is the elasticity modulus.

4. Results and Discussion

4.1. Good Agreement with the Welding Theory. In this study, the ultrasonic measurement is used to determine the residual stresses through the thickness of welded plates. The measurements are parallel to the weld axis. The values of the residual stresses relating to each weld zone are calculated from (1)–(4) while the results are shown in Figures 8, 9, 10, and 11.

The measurement results show that tensile residual stresses are generated at the weld zone and its vicinity, and compressive stresses are produced away from the weld centerline. This result is in a good agreement with the welding theory and also comparable with the results reported by Javadi et al. [24–31].

4.2. Evaluation of Residual Stresses in Different Depths. It has been observed in Figures 8–11 that the residual stresses have been decreased with increasing the measurement frequencies which could be justified by penetration depths of the L_{CR} waves. Low frequency waves travel deeper than the high frequencies (as shown in Table 1); hence the residual stresses in deeper levels of the plate would be inspected by lower frequency waves. For example, the L_{CR} wave produced by using 1 MHz transducer travels in 5 mm distance from the surface which is near the root of the main-weld pass (Figure 3). This

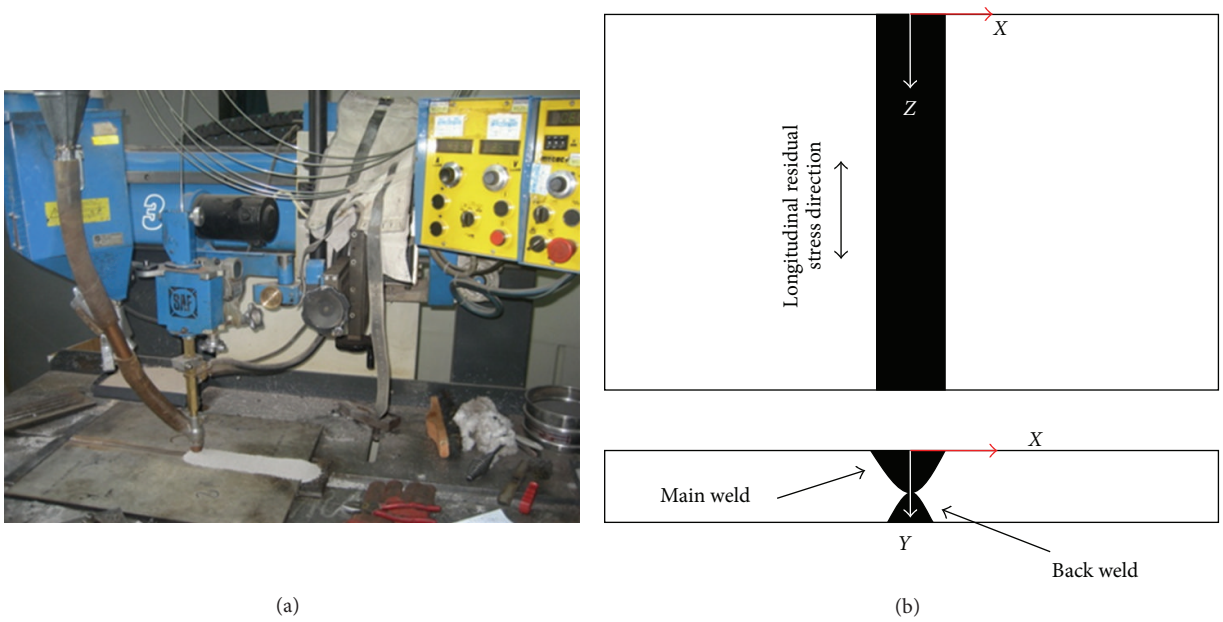


Figure 3: (a) SAW process on stainless steel plate and (b) schematic view of the welded plate.

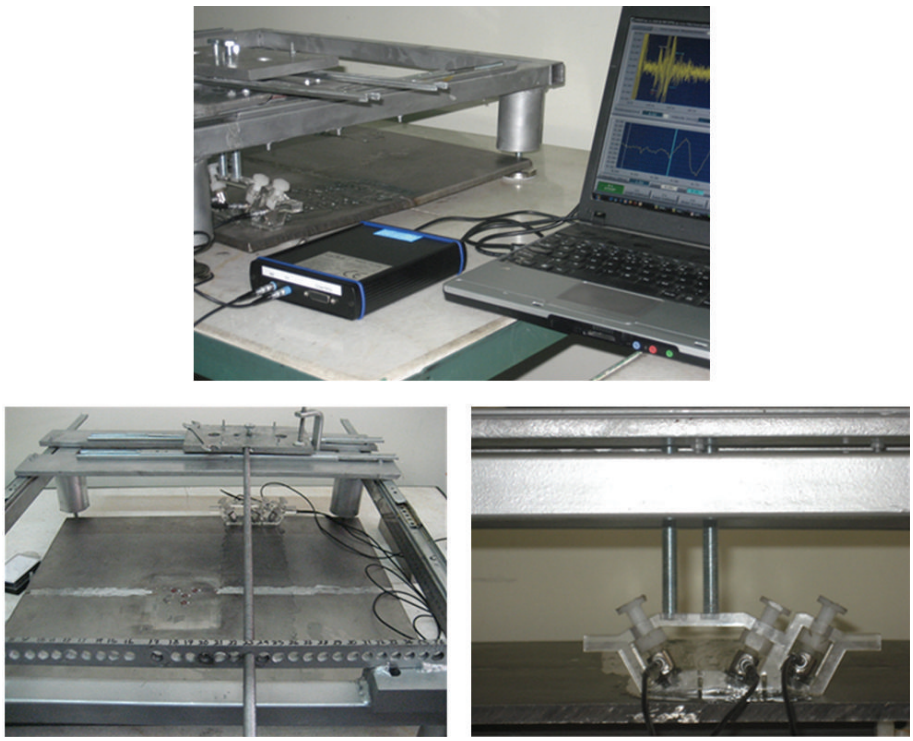


Figure 4: Measurement devices.

testing frequency measures the minimum level of residual stresses (Figure 8). This low level of measured residual stress can be justified by minimum width of the melted zone in this location where lowest thermal energy (and corresponding thermal stresses) is experienced during the welding process. Furthermore, decreasing the longitudinal residual stress by increasing the depth of plate is confirmed in different reports related to the through-thickness measuring of residual stresses [24, 32].

The residual stress on the surface measured by the 5 MHz wave is the highest (in comparison with the other testing frequencies) which is shown in Figure 11. The peak of longitudinal residual stress is occurred in the weld centerline which is comparable with the welding theory and also previous

Table 1: The results of L_{CR} depth measurement.

	1 MHz			2 MHz			4 MHz			5 MHz	
D	*A*	*T*	*D*	*A*	*T*	*D*	*A*	*T*	*D*	*A*	*T*
0	0.75	13.09	0	0.55	10.91	1	0.35	10.58	1	0.28	10.6
0.5	0.66	13.1	0.5	0.5	10.93	1.5	0.3	10.6	1.5	Noise	—
1	0.6	13.14	1	0.42	10.98	2	Noise	—			
1.5	0.54	13.18	1.5	0.4	11.02						
2	0.49	13.21	2	0.34	11.06						
2.5	0.47	13.26	2.5	Noise	—						
3	0.43	13.29									
3.5	0.42	13.33									
4	0.4	13.37									
4.5	0.33	13.37									
5	0.2	13.37									
5.5	Noise	—									

*D: depth of machining (mm); A: amplitude; T: time of flight (μs).

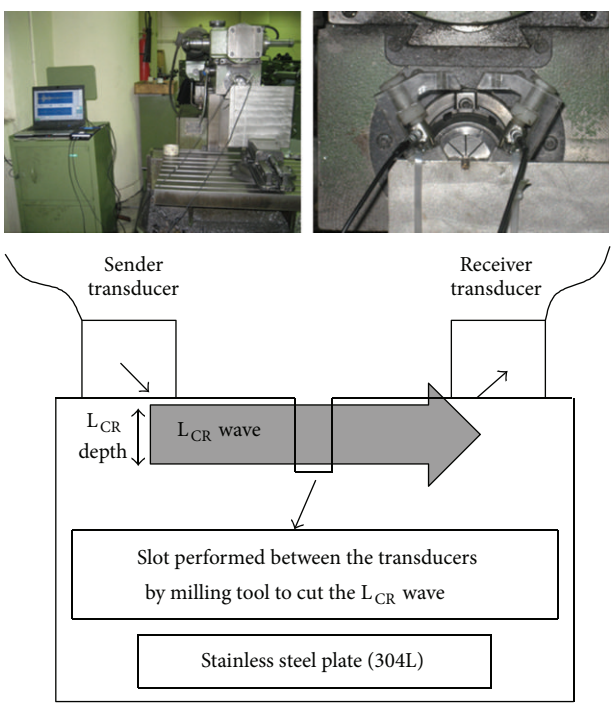


Figure 5: Experimental setup to measure depth of L_{CR} wave.

studies [24–32]. The peaks measured by 1 MHz, 2 MHz, 4 MHz, and 5 MHz transducers are equal to 82 MPa, 192 MPa, 210 MPa, and 252 MPa, respectively. It could be concluded that the amount of stress measured by using higher frequency waves is considerably increased in comparison with those obtained from low frequency measurement. Therefore the ultrasonic residual stress measurement used in this paper is capable of inspecting the welding residual stresses through the thickness of the stainless steel plates.

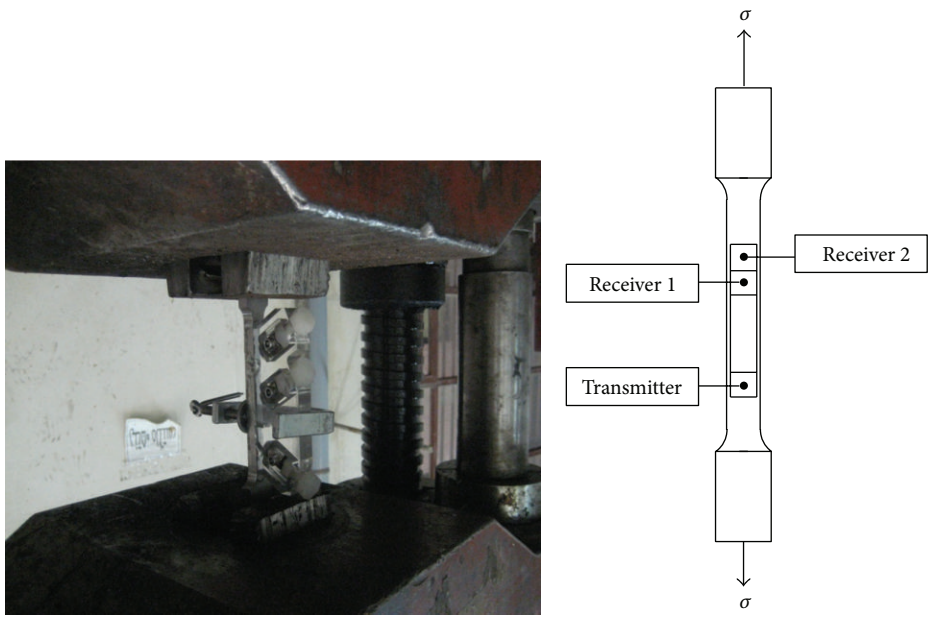
4.3. Advantages of the Ultrasonic Stress Measurement. The advantages of the ultrasonic stress measurement (performed by the L_{CR} waves) considered in this study are as in the following notes.

(1) Nondestructive method: all the stress measurements performed in this study are considered as the nondestructive measurements because there is no hole (like remaining holes after the hole-drilling method [34]) or other destructive symbols remaining on the tested plate. However, the tensile test (to measure the acoustoelastic constant) should not be considered as a destructive part of ultrasonic stress measurement process, because the acoustoelastic constant is known as a material property of the structures and could be found by using the material tables. However, finding the acoustoelastic constant for all of the materials needs the developing of the ultrasonic stress measurement method which is the goal of this study.

(2) Easy and fast: the ultrasonic measurement method is easy to use. However, some technical difficulties are available in developing the experimental setup. After organizing proper and accurate experimental devices, using this equipment needs minimum level of operators training. Furthermore, in comparison with the other stress measurement methods (like hole drilling or neutron diffraction [34]), the measurements take less time. For example, all the flight time measurements performed in this study take about 1 hour per frequencies which cover 30 points (see Figures 8–11).

(3) Portable: all of the measurement devices used in this study are considered as the portable equipment and can be employed in site.

(4) Readily available: the ultrasonic equipment could be found in many workshops and industrial organizations because the ultrasonic flaw detection is a common industrial activity. However, the L_{CR} equipment is a little different from the flaw detection devices but the principals of them are very similar. For example in



(a) (b)

FIGURE 6: Tensile test to evaluate acoustoelastic constant (L_{11}).

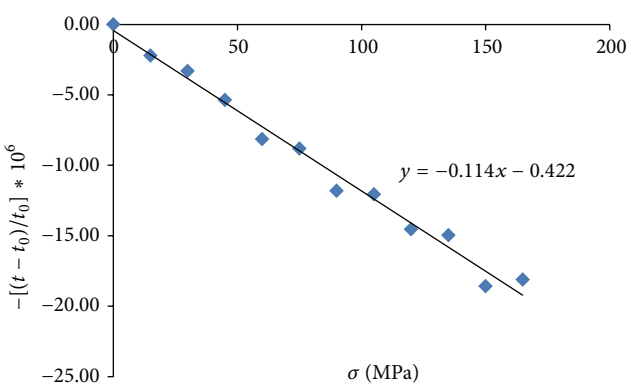


FIGURE 7: Result of tensile test to evaluate acoustoelastic constant.

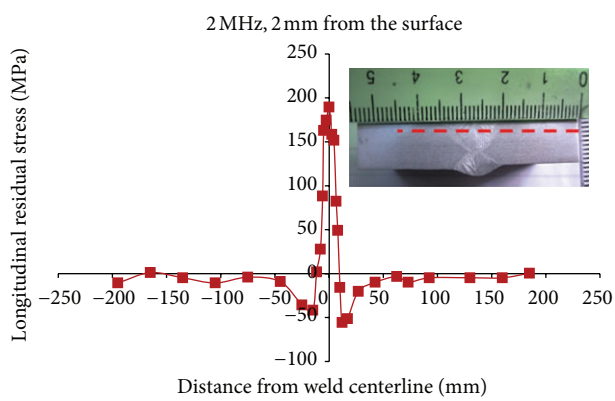


FIGURE 9: Ultrasonic stress measurement results by 2 MHz L_{CR} wave.

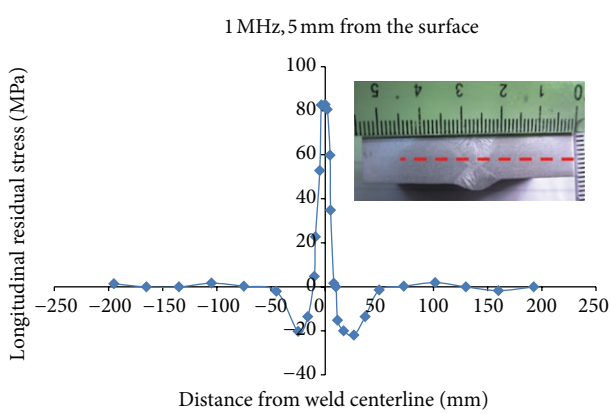


FIGURE 8: Ultrasonic stress measurement results by 1 MHz L_{CR} wave.

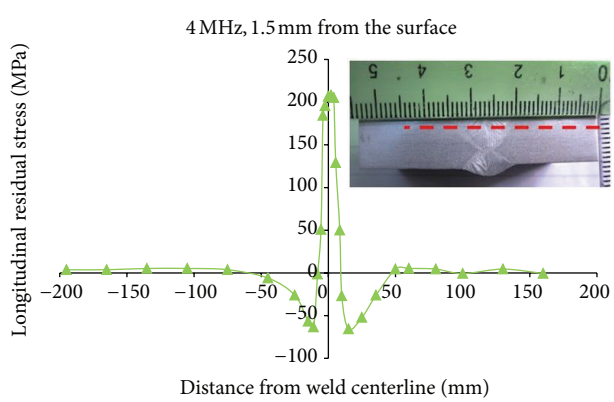


FIGURE 10: Ultrasonic stress measurement results by 4 MHz L_{CR} wave.

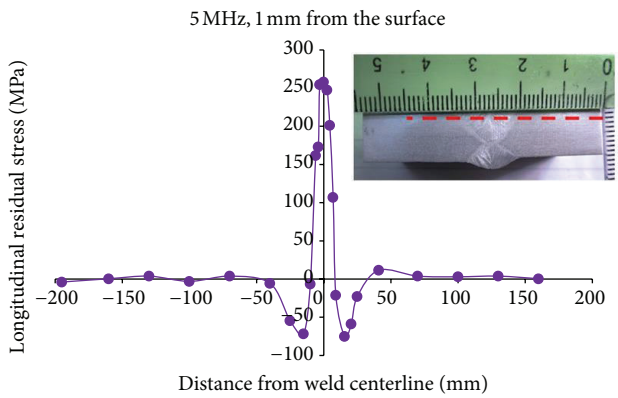


Figure 11: Ultrasonic stress measurement results by 5 MHz L_{CR} wave.

this study, normal transducers are employed, which were manufactured by a company involving in the ultrasonic flaw detection industry.

(5) Low cost: the ultrasonic equipment, in comparison with the X-ray or neutron diffraction methods [34], is available in relatively low cost. For example, all of the experimental devices employed in this study could be provided by spending less than ten thousands euro.

(6) Bulk measurement: there are some different methods (like X-ray diffraction or Barkhausen Noise [34]) capable of measuring the residual stresses nondestructively but these methods are considered as surface methods which cannot penetrate in the depth of material. While, in this study, the L_{CR} method has been confirmed as a bulk method which is capable of measuring residual stresses in different depths of the material. It is also shown in this study that it is possible to control (by changing testing frequency) how much the L_{CR} wave penetrates which leads to determining the stress level in a specified depth. The latter capability is known as a unique characterization of the L_{CR} waves introduced by Bray and Tang [33].

5. Conclusion

This paper confirms the potential of the ultrasonic method in measurement of the welding residual stresses through the thickness of the stainless steel plate. It has been shown that the residual stresses are considerably decreased by increasing the depth of measurement where the lower frequency waves can penetrate. The ultrasonic stress measurement is performed nondestructively; hence there is no damage on the tested plate by completing the stress measurement process. It has been shown that the L_{CR} method is nondestructive, easy and fast, portable, readily available, and low cost and bulk measuring technique which can be accurately employed in stress measurement of austenitic stainless steels.

Acknowledgment

The publishing has been supported by project VEGA 1/0972/11.

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