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EVALUATION OF WELDING RESIDUAL STRESS IN STAINLESS STEEL PIPES BY USING THE L_{CR} ULTRASONIC WAVES

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Abstract. *The ultrasonic residual stresses evaluation is based on the acoustoelastic effect that refers to the velocity change of the elastic waves when propagating in a stressed media. The experimental method using the longitudinal critically refracted (L_{CR}) waves requires an acoustoelastic calibration and an accurate measurement of the time-of-flight on both stressed and unstressed media. This paper evaluates welding residual stresses in welded pipe-pipe joint of austenitic stainless steel. The residual stresses in inner and outer surface of pipes were evaluated by L_{CR} ultrasonic waves by using 1 Mhz, 2 Mhz, 4 Mhz and 5 Mhz transducers. It has been shown that the difference in residual stresses between inner and outer surfaces of pipes and also between base metal and welded zone can be inspected by L_{CR} waves.*

1 INTRODUCTION

Residual stresses are present in materials without any external pressure, and normally result from deformation heterogeneities appearing in the material. 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. According to the process and temperatures reached during this operation, dangerous thermo-mechanical stresses may appear in 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 non-destructive method. The high industry request for the stress measurement techniques encouraged development of several methods like X-ray diffraction, incremental hole drilling, and the ultrasonic waves methods. Many studies showed that there is no universal or absolute method that gives complete satisfaction in the non-destructive stress monitoring of the mechanical components. Many parameters such as material, geometry, surface quality, cost, and accuracy of the measurement, etc., must be taken into account in choosing an adequate technique.

The ultrasonic technique was selected for stress measurement because it is non-destructive, easy to use, and relatively inexpensive. However, it is slightly sensitive to the microstructure effects (grains size [1], [2], [3], carbon rate [4], [5], texture [6], [7], [8], [9], and structure [10], [11], [12]) and to the operating conditions (temperature [13], [14], coupling [15], [16], 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, i.e. the acoustoelastic effect [17], [18]. The L_{CR} technique uses a special longitudinal bulk 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 authors. Brekhovskii [19], Basatskaya and Ermolov [20], Junghans and Bray [21], Langenberg et al. [22] had some detailed discussions on the characteristics of the L_{CR}.

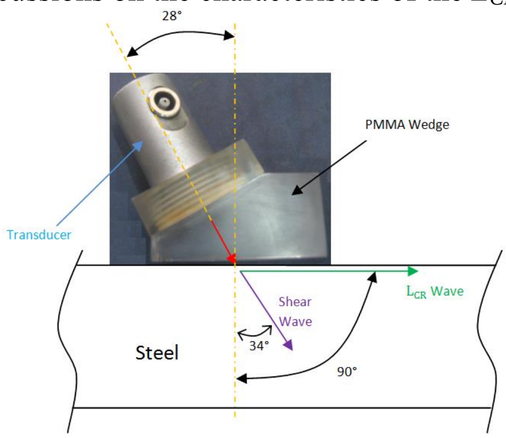

Figure 1: L_{CR} probe for PMMA (Plexiglas) wedge on steel.

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.

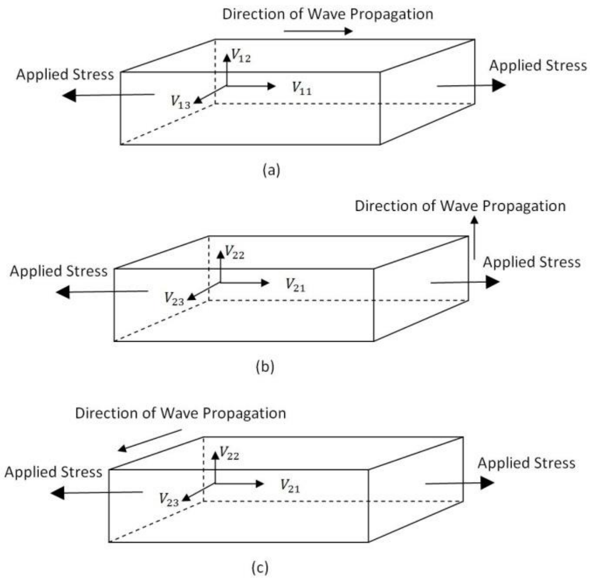

Figure 2: Velocity of plane wave and stress field in orthogonal directions [23].

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 2a 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} represents the velocity in a perpendicular plane (shear waves).

In Figure 2b and Figure 2c 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 [17] 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:

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

where ρ_o is the initial density; V_{11} is the velocity of waves in the direction 1 with particle displacement in the direction 1; λ, μ the second order elastic constants (Lame's constants); l, m, n are the third order elastic constants; $\theta = \alpha_1 + \alpha_2 + \alpha_3$ which 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 the direction 1 and υ is the Poisson's ratio. Using these values, Eq. (1) becomes:

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

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

$$\frac{dV_{11}/V_{11}}{d\varepsilon} = 2 + \frac{(\mu + 2m) + \nu\mu(1 + 2l/\lambda)}{\lambda + 2\mu} = L_{11} \qquad (3)$$

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

$$d\sigma = \frac{E(dV_{11}/V_{11})}{L_{11}} = \frac{E}{L_{11}t_0}dt \tag{4}$$

where $d\sigma$ 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 (TP304L) are commonly used for pressure vessel applications. Two passes butt-weld joint geometry without gap was performed. Two 12inch pipes with thickness of 11 mm and 34 cm length were welded in V-groove (90° included angle). Two rectangular tension test specimens were extracted from A240-TP304L plate with the same thickness and chemical composition of two pipes to determine the acoustoelastic constant.

3.2 Measurement Device

The measurement device, shown in Figure 3, includes an Ultrasonic box with integrated pulser and receiver, computer and three normal transducers assembled on a united wedge. A three-probe arrangement was used, with one sender and two receivers in order to eliminate environment temperature effect to the travel time. Twelve transducers in four different frequencies were used which their nominal frequencies were 1 Mhz, 2 Mhz, 4 Mhz and 5 Mhz. Using different frequencies helps to evaluate residual stresses through the thickness of the pipes. The diameter of all the piezoelectric elements were 6 mm. Transducers was assembled on a united PMMA wedge. The ultrasonic box is a 100 Mhz ultrasonic testing device which has a synchronization between the pulser signal and the internal clock, that controls the A/D converter. This allows very precise measurements of the time of flight – better than 1 ns.

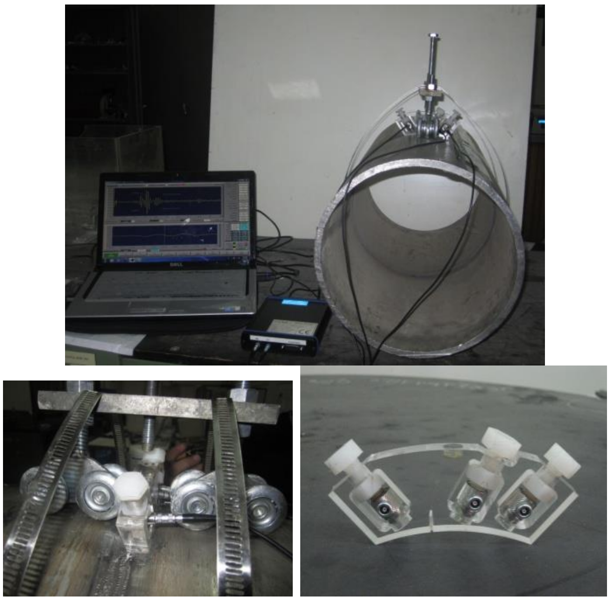

Figure 3: Measurement Devices.

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 somehow a function of frequency, with the low frequencies penetrating deeper than the high frequencies. Four different frequencies have been used in this work to evaluate the residual stress through the thickness of the pipes. Therefore depth of any frequencies should be exactly measured. The setup which is shown in Figure 4 is used here to measure the depth of the L_{CR} wave. Two transducers as sender and receiver with the same frequency are used to produce L_{CR} wave. A slot is performed between the transducers by milling tool to cut the L_{CR} wave. The depth of the slot is increased step by step and the amplitude of the L_{CR} wave is measured in each step. When the amplitude of the L_{CR} wave is equal to the noise, milling process is stopped and the depth of slot is announced as the depth of the L_{CR} waves for the tested frequency. The material used here is the same of the welded pipes. The results of this measurement are shown in Table 1. From this table it can be concluded that depth of L_{CR} wave is 5 mm, 2 mm, 1.5 mm and 1mm for transducer with nominal frequencies of 1 Mhz, 2 Mhz, 4 Mhz and 5 Mhz respectively.

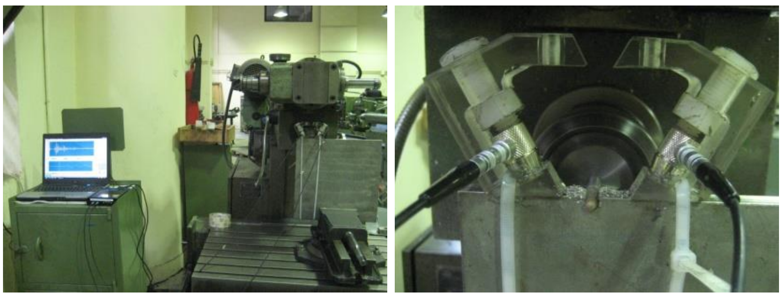

Figure 4: Experimental setup to measure depth of L_{CR} wave.

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)											

3.4 Evaluation of the Calibration Constants

To evaluate the calibration constants (acoustoelastic constant, free stress time-of-flight), the calibration samples were taken from a stainless steel 304L plate with exactly the same thickness and chemical composition of the pipes. Two rectangular tension test specimens were extracted to determine acoustoelastic constant (L_{11}) with average of the results. To evaluate the residual stress from Eq.(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 (Figure 5). Acoustoelastic constant represents the slope of the relative variation curve of the time-of-flight and the applied stress, as shown in Figure 6.

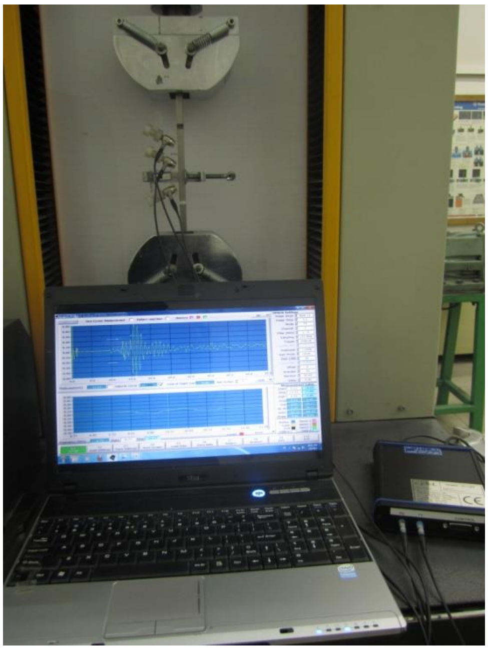

Figure 5: Tensile test to evaluate acoustoelastic constant (L_{11}).

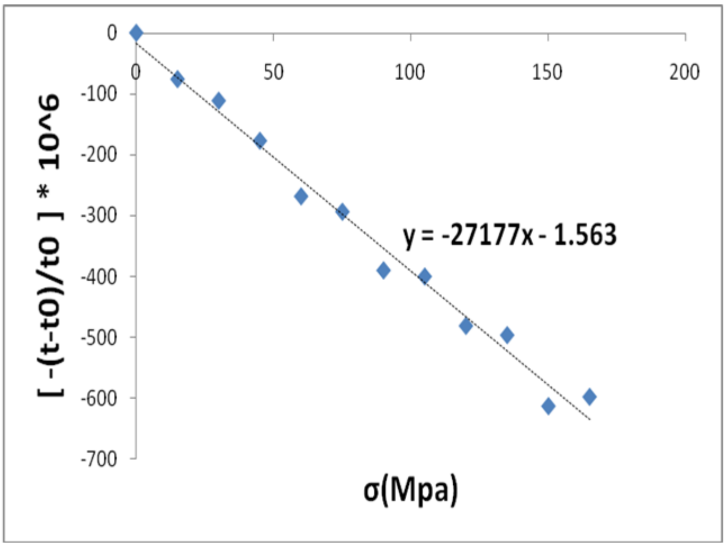

Figure 6: Result of Tensile test to evaluate acoustoelastic constant.

4 RESULTS AND DISCUSSION

In this study, the ultrasonic measurement concerns the residual stresses through the thickness of welded pipes. The measurements were parallel to the weld axis therefore the hoop residual stress of pipes is evaluated. The values of the residual stresses relating to each weld zone were calculated from the equations (1-4) and the results are shown in Figure 7 - Figure 10.

The characteristics of welding residual stress distribution in the stainless pipe are very complex especially for hoop stresses. Hoop residual stresses distribution which is shown in Figure 11-Figure 12 and has been extracted from D. Deng [24] is more popular in the references.

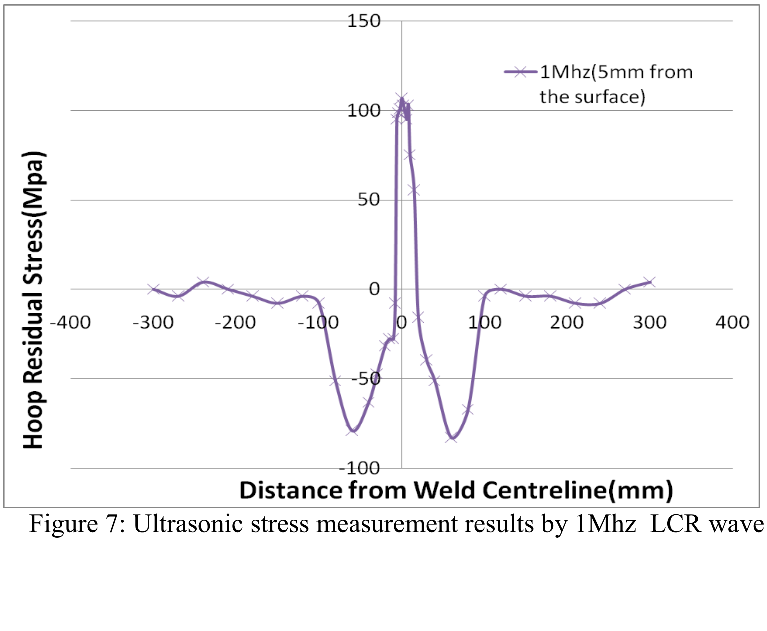

Figure 7: Ultrasonic stress measurement results by 1Mhz LCR wave.

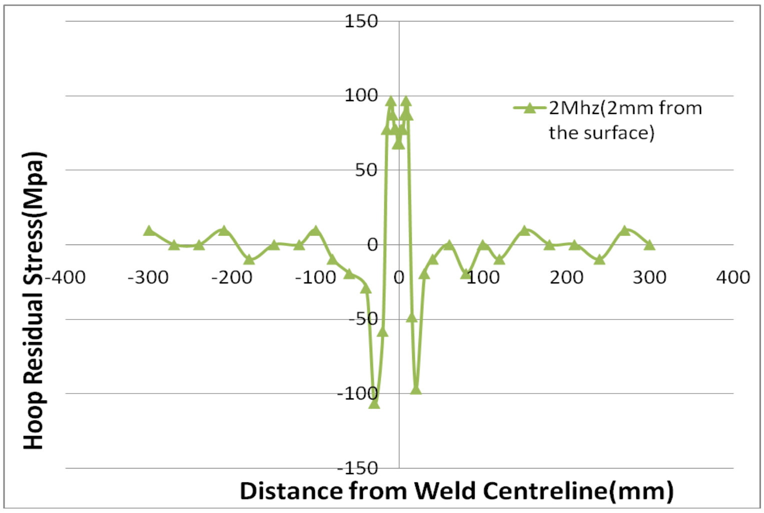

Figure 8: Ultrasonic stress measurement results by 2 Mhz L_{CR} wave.

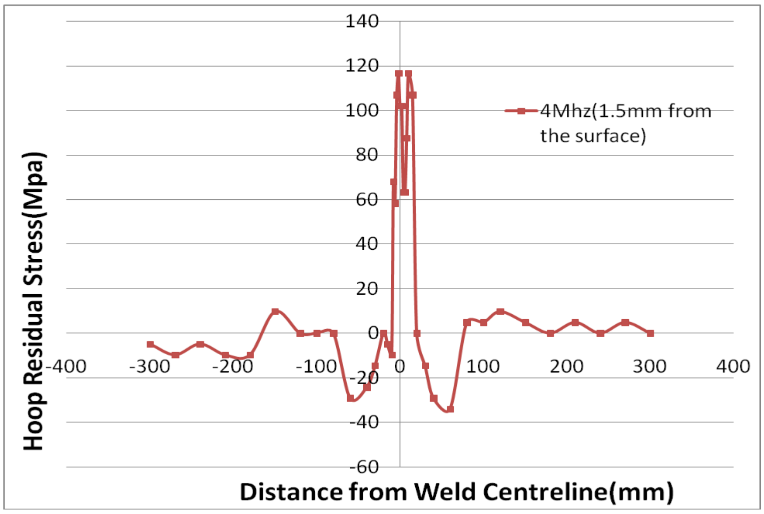

Figure 9: Ultrasonic stress measurement results by 4 Mhz L_{CR} wave.

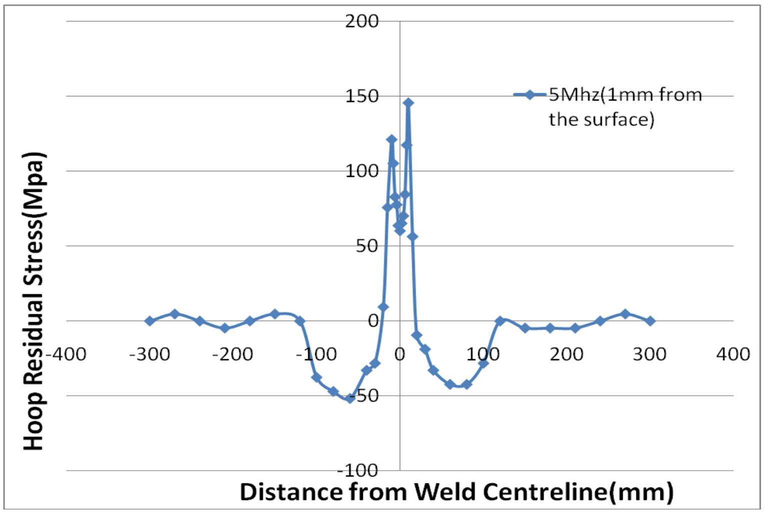

Figure 10: Ultrasonic stress measurement results by 5 Mhz L_{CR} wave.

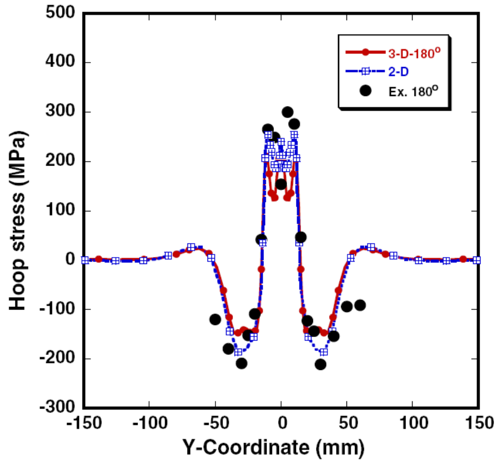

Figure 11: Hoop stress distribution on the inside surface of pipes (extracted from [24]).

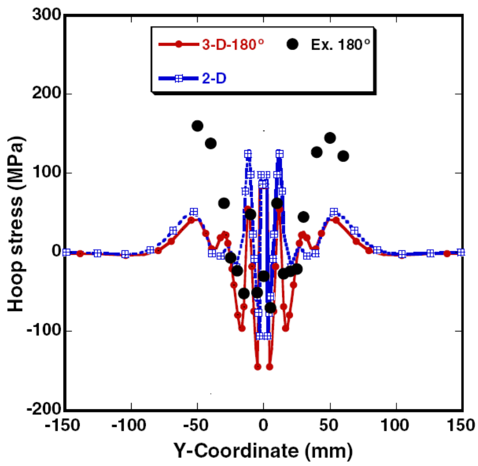

Figure 12: Hoop stress distribution on the outside surface of pipes (extracted from [24]).

Figure 11 shows that, on the inside surface, tensile hoop stresses are generated at the weld zone and its vicinity, and compressive stresses are produced away from the weld centerline [24]. But Figure 12 shows the distribution of the hoop stress on the outside surface is very complex. From the simulation and experiment results of D. Deng [24], it can be found that the shape is “like a wave and very sensitive to the distance from the weld centerline”.

Comparing Figure 11 and Figure 12 with residual stress results of this paper, shows reasonable agreement. It can be noticed that the results of 1 Mhz measurement (which is done in 5mm from the surface) is similar to the average of the inside and outside surfaces of the pipes. Because, the thickness of the pipes is 11 mm and 1 Mhz L_{CR} wave travels in the half of the thickness approximately. Also, it is obvious from Figure 8, Figure 9 and Figure 10 that with increasing the frequency (so decreasing the distance from the surface) residual stress distribution is became more similar to the hoop stress distribution on the outside surface of the pipes. In these frequencies, tensile stress exactly on the weld centerline is less than its vicinity and their difference considerably increase in high frequencies.

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 pipes.

5 CONCLUSIONS

This paper confirms the potential of the ultrasonic residual stress measurement in inspecting the welding residual stresses through the thickness of the stainless steel pipes. It has been shown that the hoop residual stress of the pipes is very complex and very sensitive to the distance from the weld centerline on the outside surface of the pipes. Near the surface of the pipes, tensile stress exactly on the weld centerline is less than its vicinity and their difference considerably increase in high frequencies. However, the L_{CR} waves can nondestructively measure the welding residual stresses of pipes.

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