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Comparison between Contact and Immersion Method in Ultrasonic Stress Measurement of Welded Stainless Steel Plates

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ABSTRACT

This study presents a comparison between contact and immersion ultrasonic method to measure welding residual stress of austenitic stainless steel plates(AISI 304L). Longitudinal critically refracted (L_{CR}) waves are employed to measure the residual stresses. By using contact and immersion transducers, a 3D distribution of longitudinal residual stress for the entire of the welded plate is presented. A finite element model of welding process, which is validated by hole-drilling method, is used to verify the ultrasonic results. The results show no considerable differences between using contact or immersion transducers in ultrasonic stress measurement of stainless steel plates, however some practical considerations are mentioned.

Keywords: Finite Element Welding Simulation; Contact Ultrasonic Stress Measurement; Immersion Ultrasonic Stress Measurement; Welding Residual Stress; Acoustoelasticity.

1- INTRODUCTION

Ultrasonic stress measurement is based on the linear relation between the ultrasonic wave velocity and the material stress. This relationship, within the elastic limit, is the acoustoelastic effect, which says that ultrasonic wave flight time varies linearly with the stress. In 1967, Crecraft[1] showed that the acoustoelastic effect can used to evaluate the stress in the engineering materials. The longitudinal critically refracted (L_{CR}) wave is a longitudinal ultrasonic wave, which can travel parallel to the surface. It is shown by Egle and Bray [2] that sensitivity of the L_{CR} waves to the strain is highest among the other types of ultrasonic waves. They also used longitudinal waves in the rail stress measurement [3]. Tang and Bray [4] used the L_{CR} waves to measure the stresses higher than yield strength and also investigated plastic deformation effect in 4140 steel. The L_{CR} ultrasonic wave was used to measure the bending stress in steel plates and bars by Bray and Tang [5]. They used two different testing frequencies (2.25 MHz and 5 MHz) and compared the results. L_{CR} measurements was done in immersion mode by Belahcene and Lu [6] to measure residual stress of S355 welded steel plate. They used hole-drilling method to verify the ultrasonic results. They also measured the penetration depth of L_{CR} by using a gauge block with different groove depth. The results showed that the penetration depth of L_{CR} wave was equivalent to one wavelength. Lu et al [7] measured welding residual stresses in the Q-235 steel and 2219 Al plates. A comparison was also made with the result of finite element method while they did not experimentally measure the stresses on the weld zone. Palanichamy et al [8] measured the residual stresses in austenitic stainless steel weld joints using ultrasonic technique.

The majority of previous studies were concerned about contact ultrasonic L_{CR} waves while the immersion and contact method are simultaneously used in this study to evaluate residual stresses. The little difference between using contact and immersion testing is previously confirmed in the ultrasonic defect detection applications. However, the difference between these methods has not been considered in the previous studies related to the ultrasonic stress measurement. It means that, finding which immersion or contact testing can be better employed for stress measurement is still under question and it is more serious problem when the L_{CR} waves are used to measure the welding residual stresses of a stainless steel structure.

Furthermore, carbon steel material was considered in most of the reviewed studies while stainless steel investigation was done in a limited scale because of its specific acoustic properties. This study investigates immersion mode in the L_{CR} measurement of austenitic stainless steels and a comparison is then performed between the immersion and contact results. By using 3axis measuring tables, it would be possible to present 3D distribution of longitudinal residual stresses in the contact and immersion ultrasonic mode. The transversal residual stresses of the welded plate, are not considered here because the residual stress amount in transverse direction reach only one-third of the value in longitudinal direction [9]. The finite element welding simulation, which is validated by hole-drilling method, is also used to verify the ultrasonic stress measurements.

2- THEORETICAL BACKGROUND

2-1. L_{CR} method

The L_{CR} method uses a longitudinal bulk wave, which travels beneath the surface at a certain depth. The L_{CR} wave will pass through an interface between two materials, only when the angle of wave incident from the first material is approximately equal to the first critical angle. According to the Snell's law, the first critical angle is calculated 28° in the case of direct contact of PMMA (Poly Methyl Methacrylate) wedge to the stainless steel and 15° in the case of immersion mode. The relation between the stress variation and time-of-flight (TOF) of the L_{CR} wave is expressed by the following equation:

$$d\sigma = \frac{E}{L_{11}}(dt / t_0) \qquad (1)$$

In the equation (1), $d\sigma$ is the stress variation, dt is TOF variation, E is the elasticity modulus and t_0 is the flight time for the wave, which travels through a stress free path in the material being investigated. For a fixed probe distance, the travel time of the L_{CR} wave decreases in compressive stress and increases in tensile stress field. L_{11} is the dimensionless acoustoelastic constant for the L_{CR} waves, which should be measured by the uniaxial tensile test.

2-2. Finite Element Welding Simulation

For numerical modeling of the welding residual stresses, one needs to take account of the mechanical behavior of welds, which is sensitive to the close coupling between heat transfer, microstructure evolution and thermal stress analysis. The problem is formulated as a successively coupled thermal stress analysis. First, a non-linear thermal analysis is performed to calculate the temperature history of the entire domain. Then, the results of the thermal analysis are applied as a thermal body load in a non-linear mechanical analysis determining residual stress and distortion. The finite element (FE) models for both thermal and structural analysis are the same.

The general-purposed FE program ANSYS is used for the analyses. As no metallurgical transformation occurs in the austenitic stainless steel (304L), the detailed modeling of the cooling phase transformation is not considered. In the present study, the double ellipsoid heat source pattern proposed by Goldak et al. [10] is used. The material parameters young's modulus, poisson's ratio, yield stress, strain hardening and heat expansion coefficient are temperature dependent.The material properties of 304L stainless used in the finite element analysis is extracted from Zhu et al [11].

A conventional technique named "Element Birth and Death"[12] is used for modelling of the deposited weld. A complete FE model is generated in the start of the analysis. However, all elements representing the deposited weld, except elements for the tack welds, are deactivated by assigning them a very low stiffness. During the thermal analysis, all the nodes of deactivated elements (excluding those shared with the base metal) are also fixed at room temperature till the birth of the respective elements. Deactivated elements are reactivated sequentially when they come under the effect of the welding torch. Linear elements are preferred than higher-order elements in non-linear problems of this type [13]. Here, eight-noded-brick elements with linear shape functions are used in the FE modeling. The basic FE model of plate is shown in Fig.1, while only one side of the welded plates is modeled with the symmetry assumption.

3- EXPERIMENTAL PROCEDURES

3-1. Sample Description

Tested material is austenitic stainless steel plate (A240-TP304L). Single pass butt-weld joint geometry with a back-weld pass and without root gap is used. Two 600×250×10 mm normalized and rolled plates are welded in V-groove (90° included angle). Back and the main weld passes are performed by submerged arc welding (SAW) process while the ER308L is used as electrode.

3-2. Measurement setup

The measurement setup, used for the contact mode shown in Fig.2, includes an ultrasonic box, computer and contact transducers. In addition, a 3axis moving table is employed to move transducers accurately and with enough stability. The ultrasonic box is a 100 MHz (sampling frequency) ultrasonic testing device which has synchronization between the pulser signal and the internal clock, which controls the A/D converter. Its post trigger (delay) time has stability within the range of 1 ns which is achieved by employing an internal clock with frequency of 1 GHz. The high stability of ultrasonic box is claimed by the device manufacturer however, this stability is experimentally measured in this study and has been confirmed. Three 2 MHz normal transducers are assembled on an integrated wedge to measure the time of flight. A poly methyl methacrylate (PMMA) material, under the trademark Plexiglas, is cut by laser cutting to construct the wedge. A three-probe arrangement is used, with one transmitter and two receivers in order to eliminate environmental effect on the travel time.

The measurement setup, used for the immersion mode shown in Fig.3, includes an automated 3axis moving table and a time of flight (TOF) measuring element. The ultrasonic box, ultrasonic software and computer are the same as those of the contact mode setup. The automated moving table makes possible to move the TOF measuring element with 1µm. TOF measuring element includes two 2 MHz immersion transducers assembled on an integrated wedge to measure the time of flight. Because of welding deformations in the surface of the plates, the gap between transducers and tested plate is changed when the TOF measuring element moves. To eliminate effect of these changes on the measured TOF, a dial indicator is used to keep the distance constant.

3-3. Determination of L_{CR} Penetration Depth

When the L_{CR} technique is applied to an application with limited wall thickness, the penetration depth of the L_{CR} wave is expected to be a function of frequency. However, there is no definite relation between L_{CR} depth and frequency. Hence, the L_{CR} depth should be measured experimentally. The setup, which is shown in Fig.4, is used to measure penetration depth of the L_{CR} wave. A variable depth groove is cut in a plate, with the same material and thickness of the tested plate, to produce a barrier to physically prevent the L_{CR} wave from reaching the receiver transducer. It is found that a 2 mm depth groove could completely prevent a 2 MHz L_{CR} wave to pass in the both contact and immersion modes, which indicates that the penetration depth of such a L_{CR} wave is 2mm.

It has been emphasized by Egle and Bray [5] that the penetration depth for L_{CR} wave is not the same as that defined for the Rayleigh wave, which travels on the surface and has peak energy propagation within one wavelength depth. It means that the L_{CR} wave can penetrate more (or less) than one wavelength in the depth. The wavelength related to the 2 MHz wave is measured equal to 2.95 mm while, the penetration depth is measured equal to 2 mm which is less than one wavelength. The ultrasonic examination of austenitic stainless steel is usually associated with some practical difficulties such as ultrasound attenuation, beam skewing and beam scattering. The low penetration depth measured here, can be justified by the practical difficulties in the ultrasonic inspection of austenitic stainless steels. However, according to the results reported by Egle and Bray [5] or Javadi et al [14], the penetration depth of L_{CR} waves is not necessarily equal to one wavelength.

Furthermore, the penetration depth depends on the transducer size and L_{CR} propagation distance as well as frequency. Hence, the penetration depth measured in this study is limited to the wedge and transducer dimensions shown in Fig.5. The propagation distance between the transmitter and first receiver is equal to 2.76 cm while it is 6.16 cm for the second receiver. The results of penetration depths measured by Javadi et al [14] also confirms that the 2 MHz L_{CR} wave penetrates 2 mm in depth. The measurement method employed by Javadi et al [14] was completely different from experimental method used in this study while the transducer dimensions and L_{CR} propagation distance were same as the dimensions shown in Fig.5. In their experimental setup, a slot was cut between the transducers by milling tool to produce an obstacle in the path of the L_{CR} wave. The depth of the slot was increased step by step and the amplitude of the L_{CR} wave was measured in each step. When the amplitude of the L_{CR} wave was equal to the noise, milling process was stopped while the depth of slot represented the penetration depth of the L_{CR} waves which was measured 2 mm for the 2 MHz L_{CR} wave [14]. Comparing the result of their work with this study, shows that using different experimental setup reach to same penetration depth results which could be considered as a validation for penetration depth measurements.

3-4. Evaluation of the Acoustoelastic Constants

To evaluate the acoustoelastic constant (L_{11}), the tensile test samples are taken from both sides of the plate. Rectangular tensile test specimens are extracted from parent material (PM), melted zone (MZ) and heat affected zone (HAZ) separately. Metallographic analysis of the weld shows that the HAZ is not large enough to extract tensile test sample. Therefore, samples are prepared from tensile test specimens (extracted from the PM) to reproduce microstructure of HAZ by means of heat treatment. The samples are exposed to different annealing temperature, annealing time, cooling rate and cooling environment. Microstructure of each sample is then investigated and the one most similar to the HAZ microstructure is selected to be used as the tensile test sample of HAZ.

All of the tensile test specimens are also extracted parallel to the weld, which is parallel to propagation direction of the L_{CR} wave, to consider to the effect of material tissue on the acoustoelastic constant measurement. The material tissue is affected by the rolling direction of the tested plate which leads to some differences in the acoustoelastic constant measured parallel or perpendicular to the rolling direction. Hence, the acoustoelastic constant cannot be accurately evaluated on the samples extracted in directions which are different from the L_{CR} wave propagation because of tissue effect.

To evaluate the residual stress according to equation (1), the value t_0 is measured directly from the stress-free samples. The acoustoelastic constant (L_{11}) is then deduced experimentally from a uniaxial loading calibration associated to the contact and immersion setup separately (Fig.6 and Fig.7).

However, using the C-clamp in the tensile test can lead to a little measurement error in contact acoustoelastic constant evaluation (Fig.6). The thickness of tensile test specimen is decreased with increasing the tensile stress which leads to losing the pressure of C-clamp on the transducers. The pressure loss of C-clamp is the reason for reducing the amplitude of L_{CR} wave during the tensile test which creates a little error in acoustoelastic constant measurement. These practical difficulties could be better controlled by replacing the C-clamp with a hydraulic pressure system. Furthermore, it is expected to reach more precise measurement related to the immersion acoustoelastic constant because the clamping system is not employed during the tensile test (Fig.7).

4- RESULTS AND DISCUSSION

The results of tensile test are shown in Fig.8 for contact and immersion acoustoelastic constant. The contact and immersion L_{11} constant are listed in Table 1, according to the PM, HAZ and MZ. The acoustoelastic constant of the parent material is higher than that of the HAZ while the weld shows the maximum constant. The results show no significant difference between the values of the L_{11} constant measured by contact and immersion methods. However, because of measures have to be taken against water leakage during the tensile test, the L_{11} constant measuring process in the immersion method is rather more difficult than in the contact one.

In this study, the 3D finite element analysis for welding simulation is verified by hole-drilling method. The validated finite element model can be used to predict the residual stresses. The residual stresses are also measured with L_{CR} ultrasonic waves. Eight Test-Sections as shown in Fig.9 are selected to compare the results obtained from ultrasonic and FE methods.

It should be noted that both contact and immersion ultrasonic methods measure the average of stresses in a determined depth. It means that in the case of 2 MHz L_{CR} wave, which travels within 2 mm layer of the surface, gives the average of residual stress in this zone. Hence, in the FE method, the average of residual stresses for all the nodes located in the range of 0-2 mm under the surface are calculated to compare with those obtained from ultrasonic measurements. The 3D distribution of longitudinal residual stresses analyzed by FE simulation is shown in Fig.10. The 3D graph is produced by the longitudinal residual stresses of eight weld cross sections according to the Test Sections shown in Fig.9.

For verification of FE model, hole-drilling test is performed in four different points according to the Fig.11. The average results of FE residual stress in 2 mm surface layer are in good agreement with those of hole-drilling. It should be noticed that, hole-drilling method is also gives the average of residual stress measured along the 2 mm depth hole.

The 3D distribution of ultrasonic measurement is shown in Fig.12 and Fig.13 according to the contact and immersion mode respectively. The immersion results seem to be smoother than those obtained from contact measurements. It can be justified by elimination of couplant and clamping system during the tensile test along with using automated 3axis moving table in the immersion measurement setup.

Fig.14 compares experimental results with the FE modeling results for eight different test sections. The maximum deviation between contact and immersion measurements with FE results are listed in Table 2.

The results of contact and immersion ultrasonic measurements show an acceptable agreement with finite element analysis. The deviation is less than ±16 MPa, which is about 8 percent of the yield strength according to the tested material. The results also show that the immersion measurements are in better agreement with FE results. The average of deviation with FE results is 7.15 MPa and 13.27 MPa for the immersion and contact measurements respectively (according to the Table 2).

Using the ultrasonic couplant between wedge and tested plate is eliminated in immersion measurement. This leads to results, which are more accurate in the case of immersion method. Using the clamping system during the tensile test is a reason for higher measurement error of contact acoustoelastic constant which leads to less accurate results of contact ultrasonic stress measurement. Furthermore, employing the automated 3axis moving table with 1µm resolution in the immersion method may be thought as another reason for obtaining better results. Test time for the immersion method is higher than contact measurements because of setting the dial indicator in all of the measured points. Using the second receiver is not necessary in the immersion measurements because the environmental effects on the TOF are more controllable than contact test. The experimental devices of immersion mode are more expensive than contact setup.

5- CONCLUSION

The main goal of this study is comparison of contact and immersion ultrasonic method in residual stress measurement of the stainless steel plate with 10 mm thickness. Finite element welding simulation, hole-drilling method, contact L_{CR} ultrasonic waves and immersion L_{CR} ultrasonic waves are employed to reach this goal. According to achieved results, it can be concluded that:

1) The averages of FE results in a 2 mm depth are in the good agreement with those of hole-drilling method.
2) There is no significant difference between the values of acoustoelastic constants measured by contact and immersion methods.

3) The results of contact and immersion ultrasonic measurements show an acceptable agreement with finite element analysis.

4) The immersion measurements are in better agreement with FE results in comparison with those of contact method.

5) The environmental effects on the TOF are more controllable in the immersion measurements in comparison with the contact method.

Despite the above considerations, there is no significant difference between contact and immersion L_{CR} waves in the ultrasonic stress measurements of stainless steels. Both of them can measure the residual stress with an acceptable accuracy. Selecting between them depend on geometry and dimensions of tested structure and the available experimental devices.

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7- TABLES

Table 1: The Contact and Immersion L_{11}constant

	Parent Material (PM)	Heat Affected Zone (HAZ)	Melted Zone (MZ)
Contact L_{11} constant	2.102	1.839	2.452
Immersion L_{11} constant	2.14	1.77	2.387

Table 2: Maximum deviation between contact and immersion measurements with FE results

	Test Section 8	Test Section 7	Test Section 6	Test Section 5	Test Section 4	Test Section 3	Test Section 2	Test Section 1	Average
Maximum deviation between contact measurements with FE results (MPa)	15.65	11.24	12.96	12.94	15.05	12.64	13.22	12.47	13.27
Maximum deviation between immersion measurements with FE results (MPa)	7.66	6.32	8.15	5.54	9.42	10.23	4.52	5.37	7.15

8- LIST OF FIGURE CAPTIONS

Fig.1. Basic FE model

Fig.2. Contact Measurement Devices

Fig.3. Immersion Measurement Devices

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

Fig.5. Dimensions of (a) PMMA Wedge and (b) Transducer

Fig.6. Tensile test to evaluate contact acoustoelastic constant

Fig.7. Tensile test to evaluate immersion acoustoelastic constant

Fig.8. Result of Tensile test to evaluate (a) contact acoustoelastic constant and (b) immersion acoustoelastic constant

Fig.9. Test Sections in Contact Ultrasonic Measurement

Fig.10. 3D Distribution of FE Results according to the Average of Residual Stress in 2 mm from the Surface

Fig.11. The Comparison of Finite Element and Hole Drilling Method

Fig.12. 3D Distribution of Contact Ultrasonic Measurements according to the Longitudinal Residual Stress

Fig.13. 3D Distribution of Immersion Ultrasonic Measurements according to the Longitudinal Residual Stress

Fig.14. Comparison of FE with Contact and Immersion Ultrasonic Results according to the Test Section

9- FIGURES

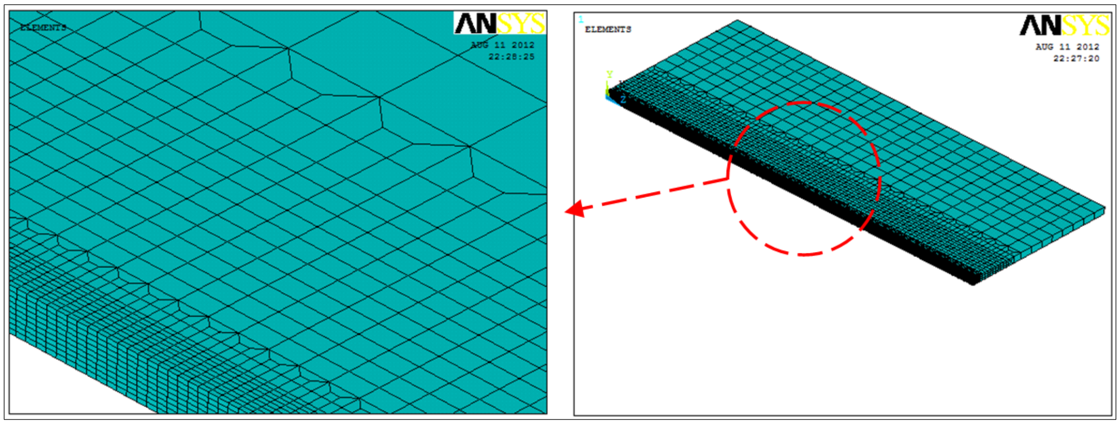

Fig.1. Basic FE model

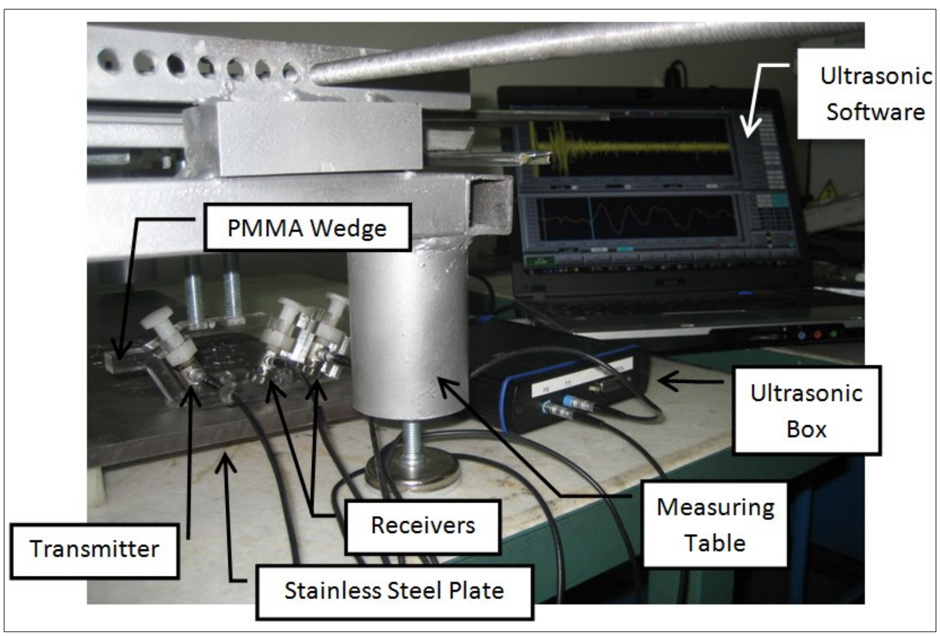

Fig.2. Contact Measurement Devices

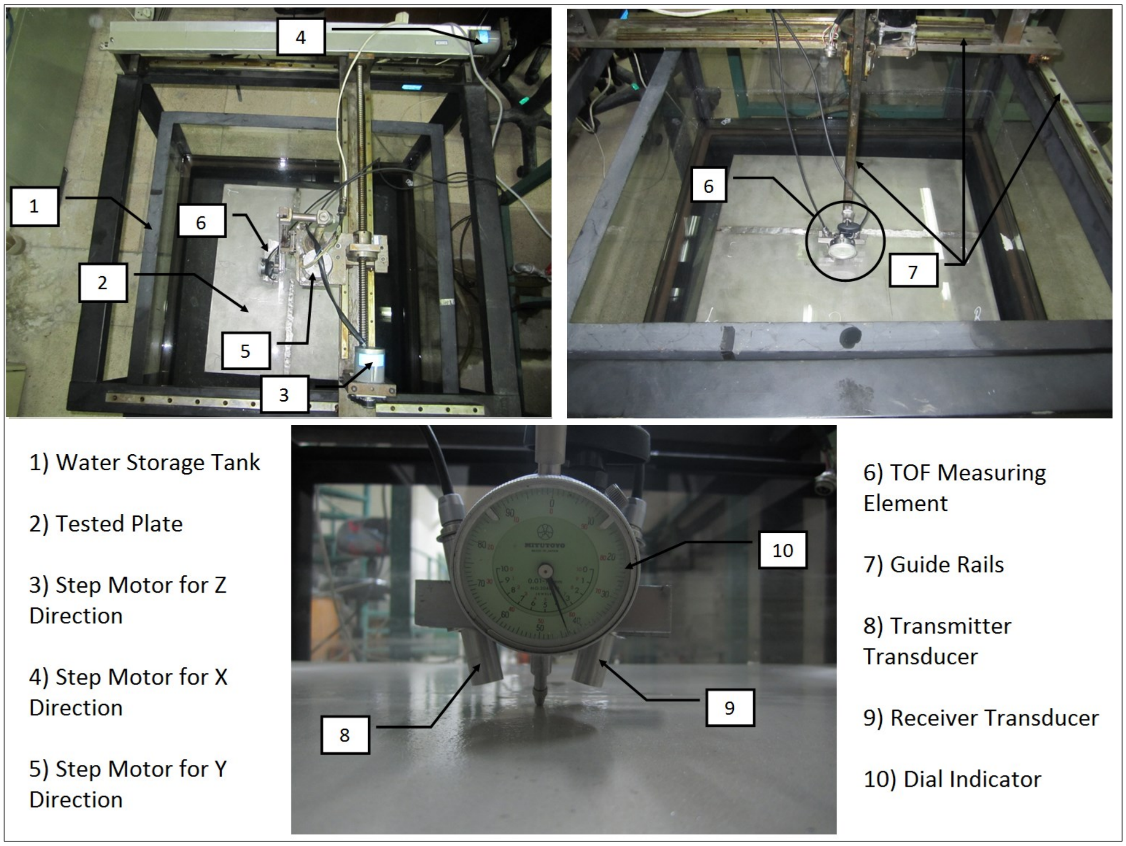

Fig.3. Immersion Measurement Devices

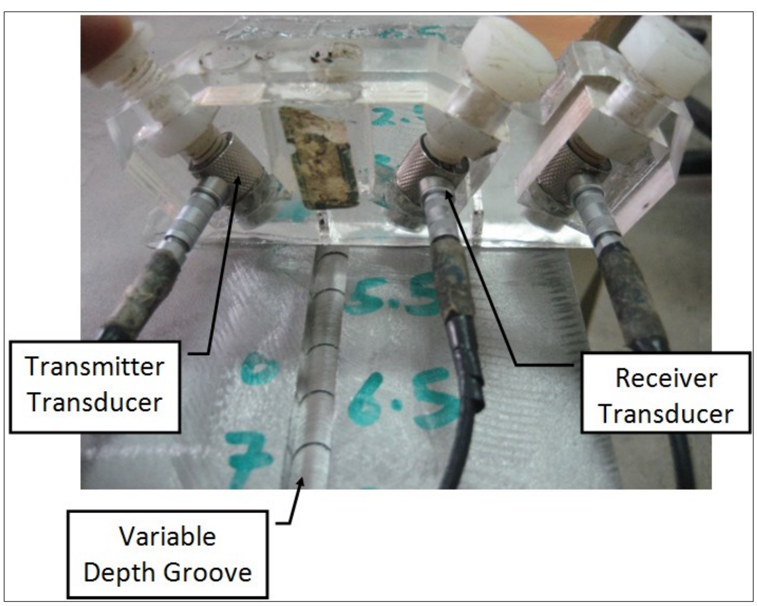

Fig.4. Experimental setup to measure depth of L_{CR} wave

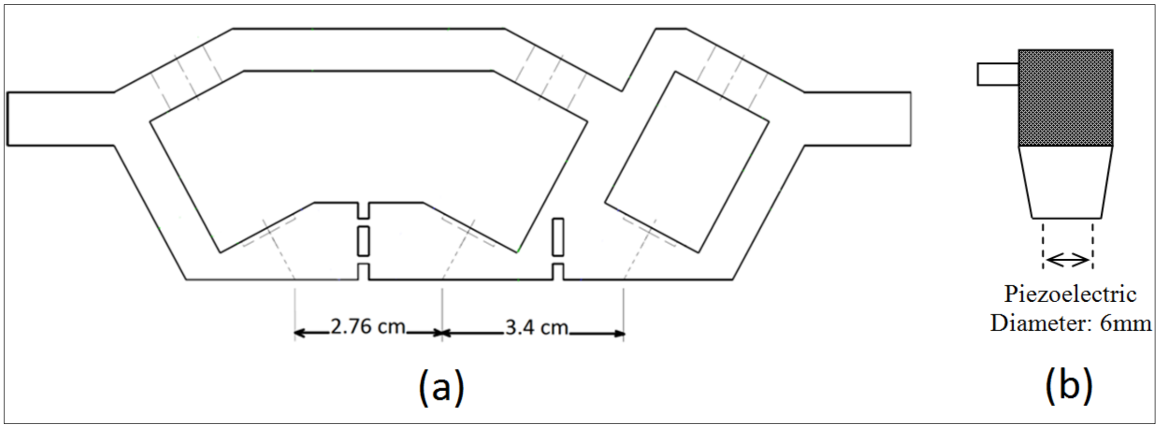

Fig.5. Dimensions of (a) PMMA Wedge and (b) Transducer

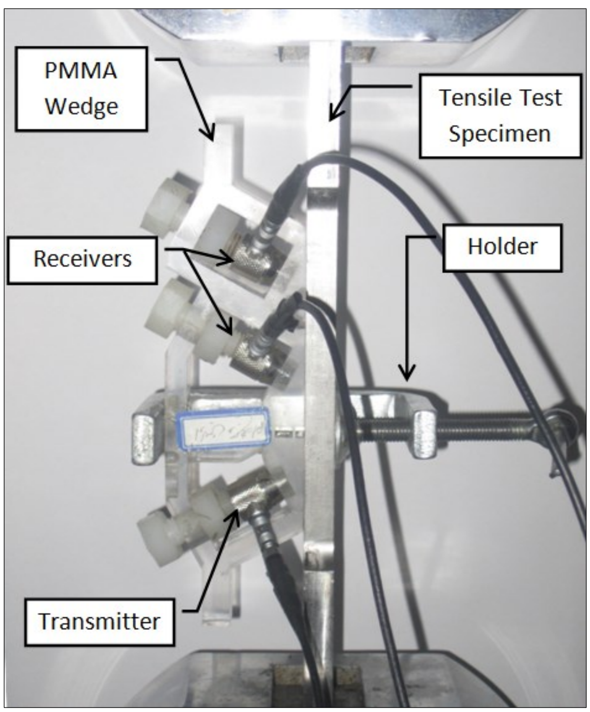

Fig.6. Tensile test to evaluate contact acoustoelastic constant

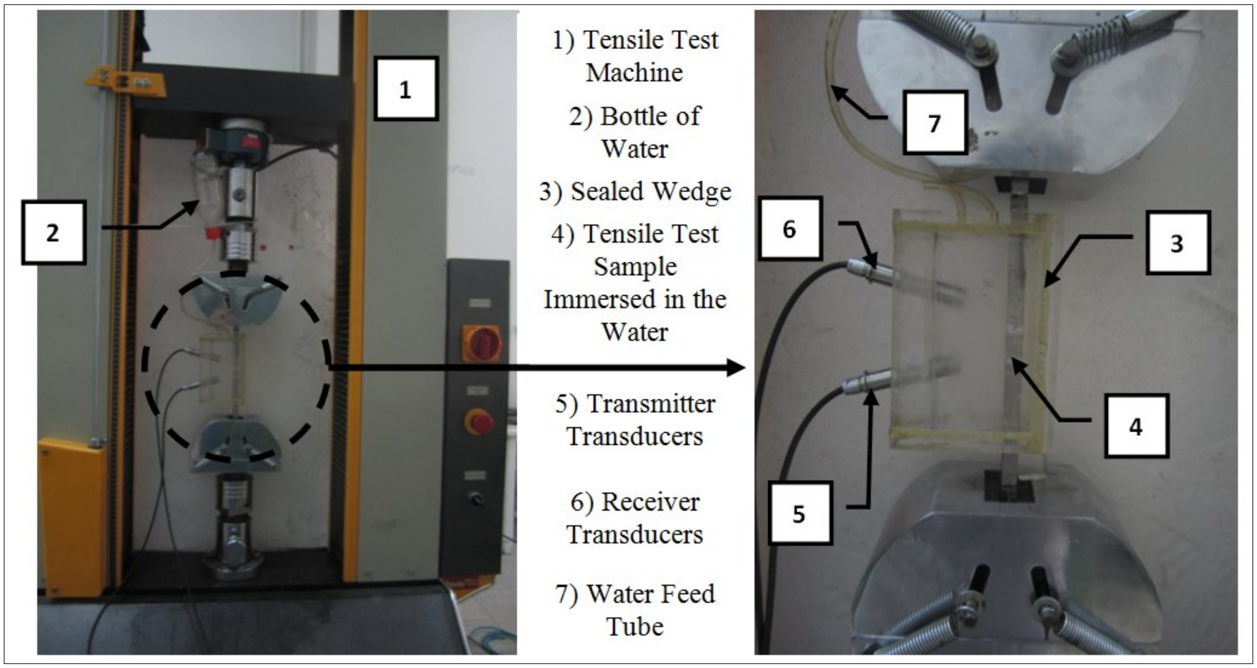

Fig.7. Tensile test to evaluate immersion acoustoelastic constant

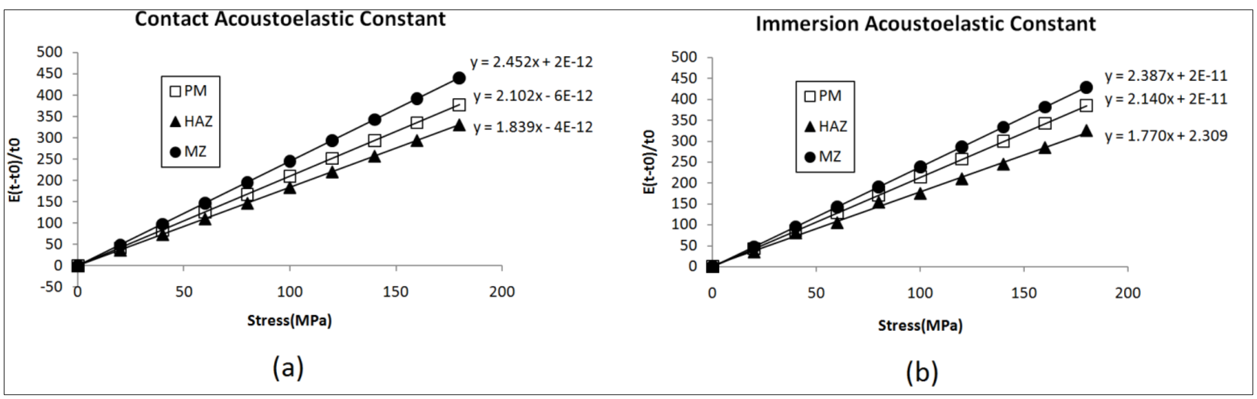

Fig.8. Result of Tensile test to evaluate (a) contact acoustoelastic constant and (b) immersion acoustoelastic constant

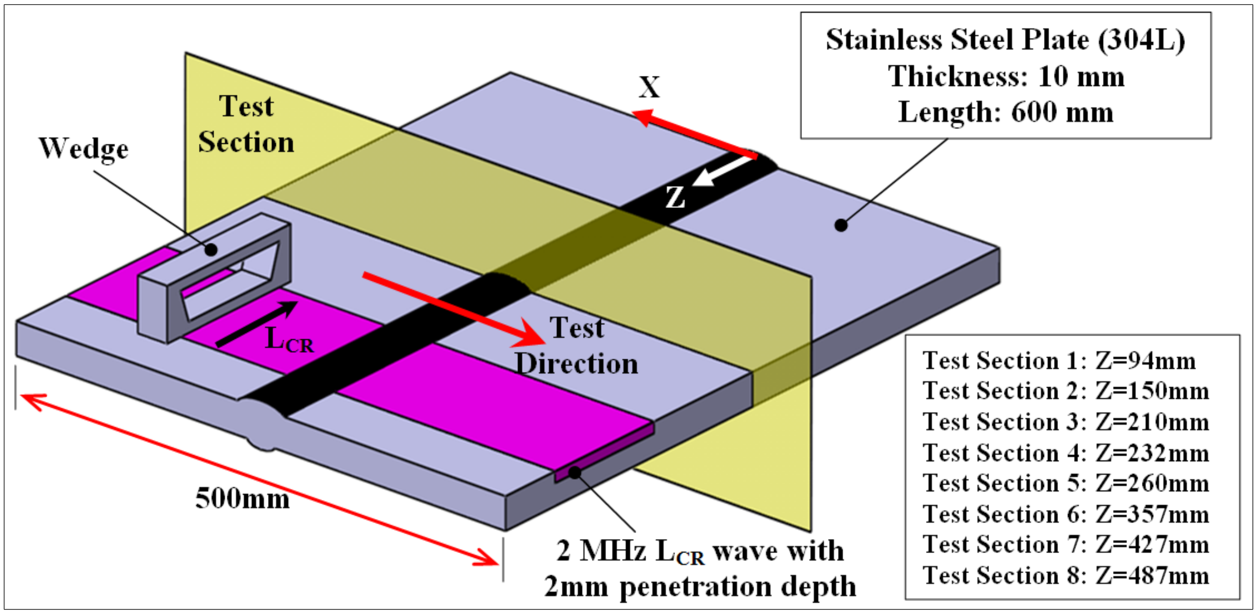

Fig.9. Test Sections in Contact Ultrasonic Measurement

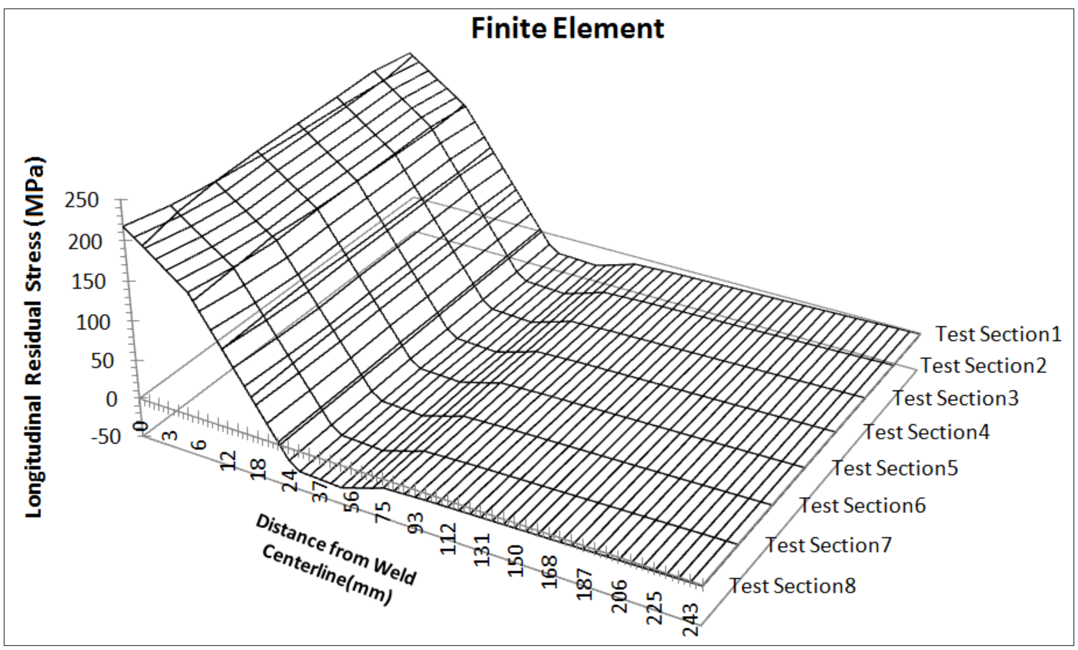

Fig.10. 3D Distribution of FE Results according to the Average of Residual Stress in 2 mm from the Surface

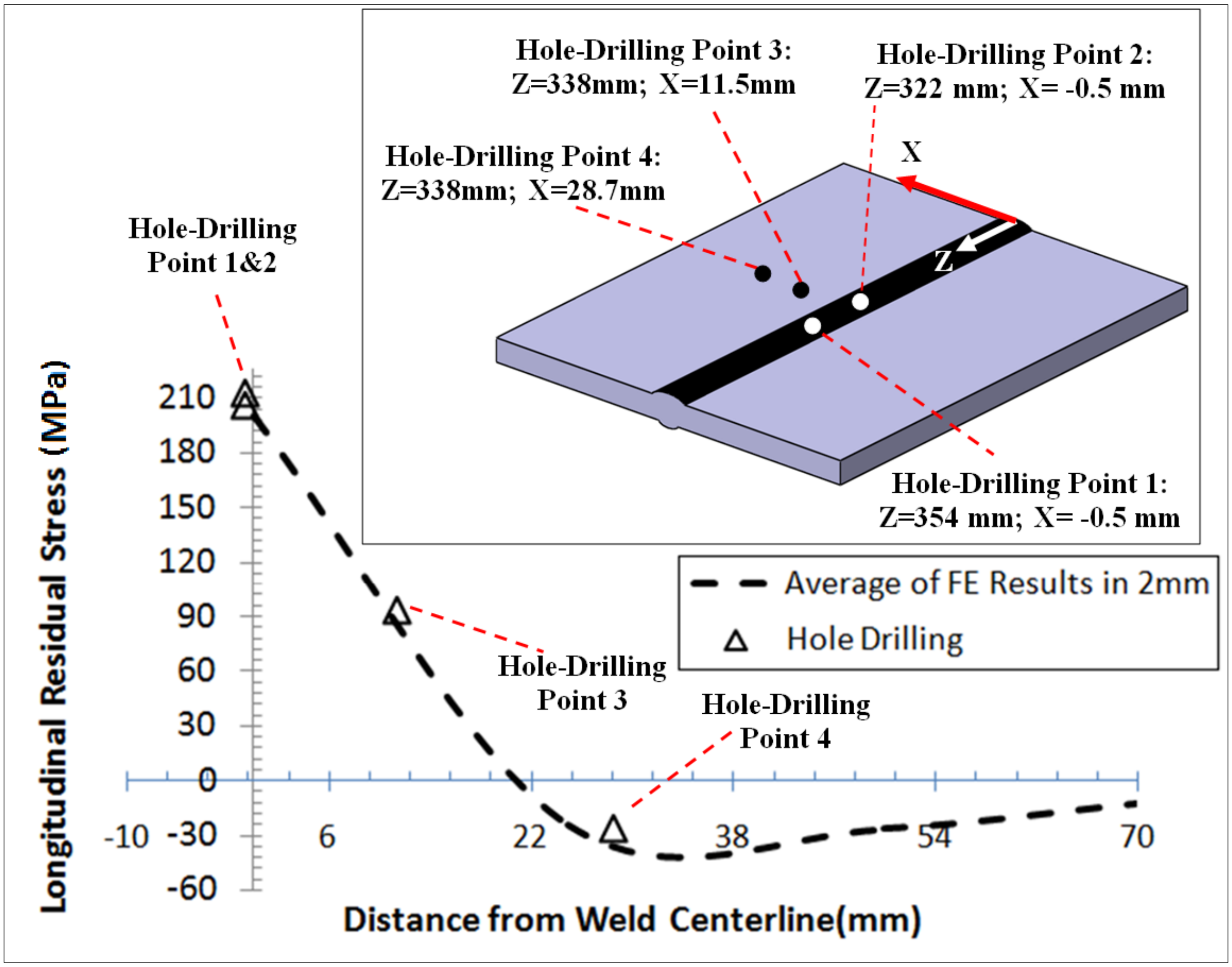

Fig.11. The Comparison of Finite Element and Hole Drilling Method

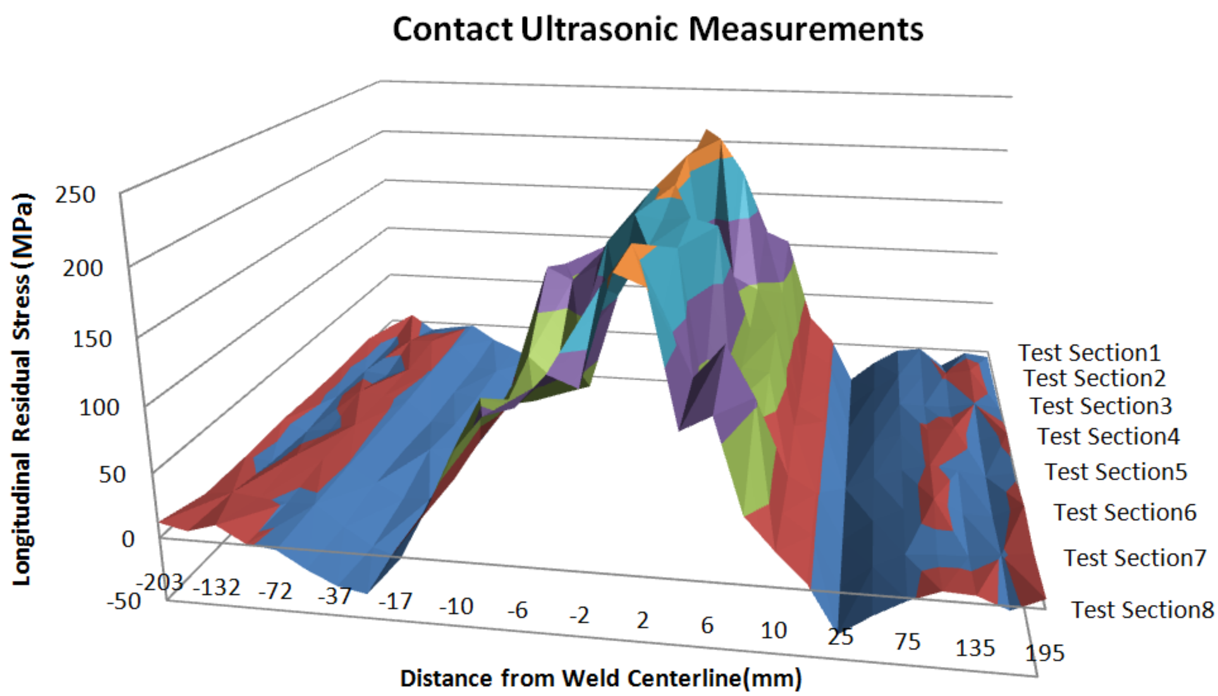

Fig.12. 3D Distribution of Contact Ultrasonic Measurements according to the Longitudinal Residual Stress

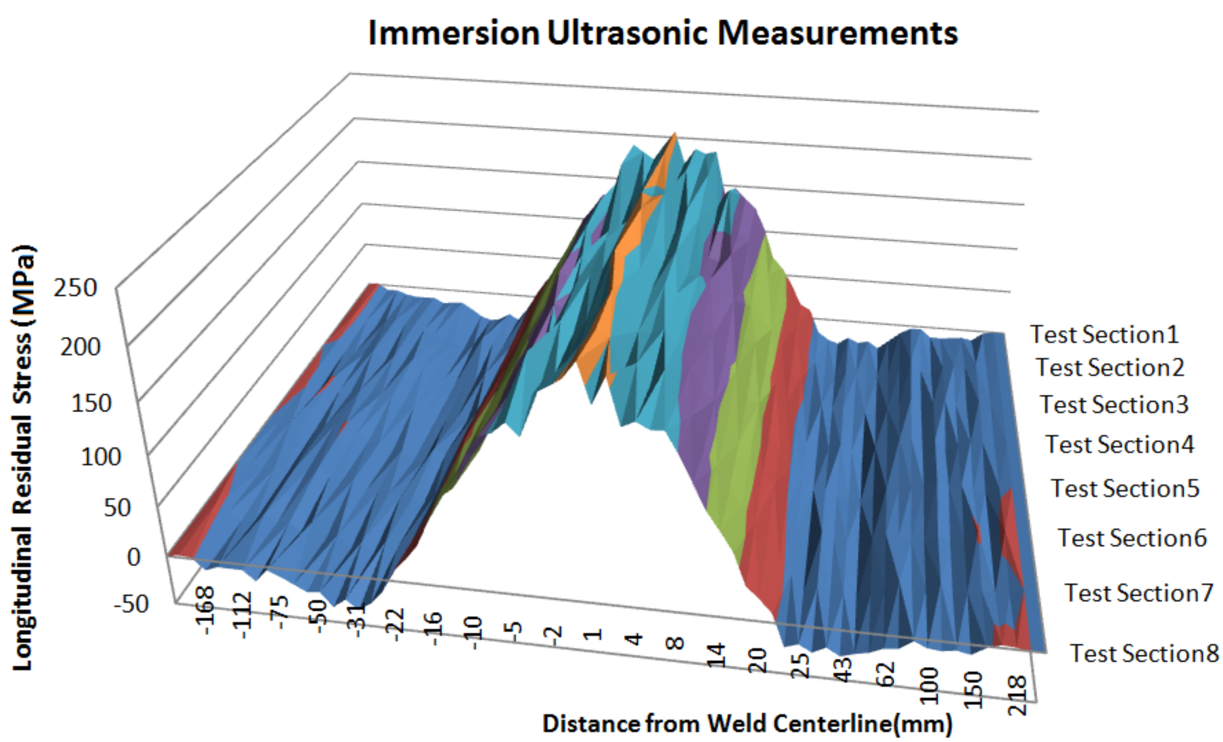

Fig.13. 3D Distribution of Immersion Ultrasonic Measurements according to the Longitudinal Residual Stress

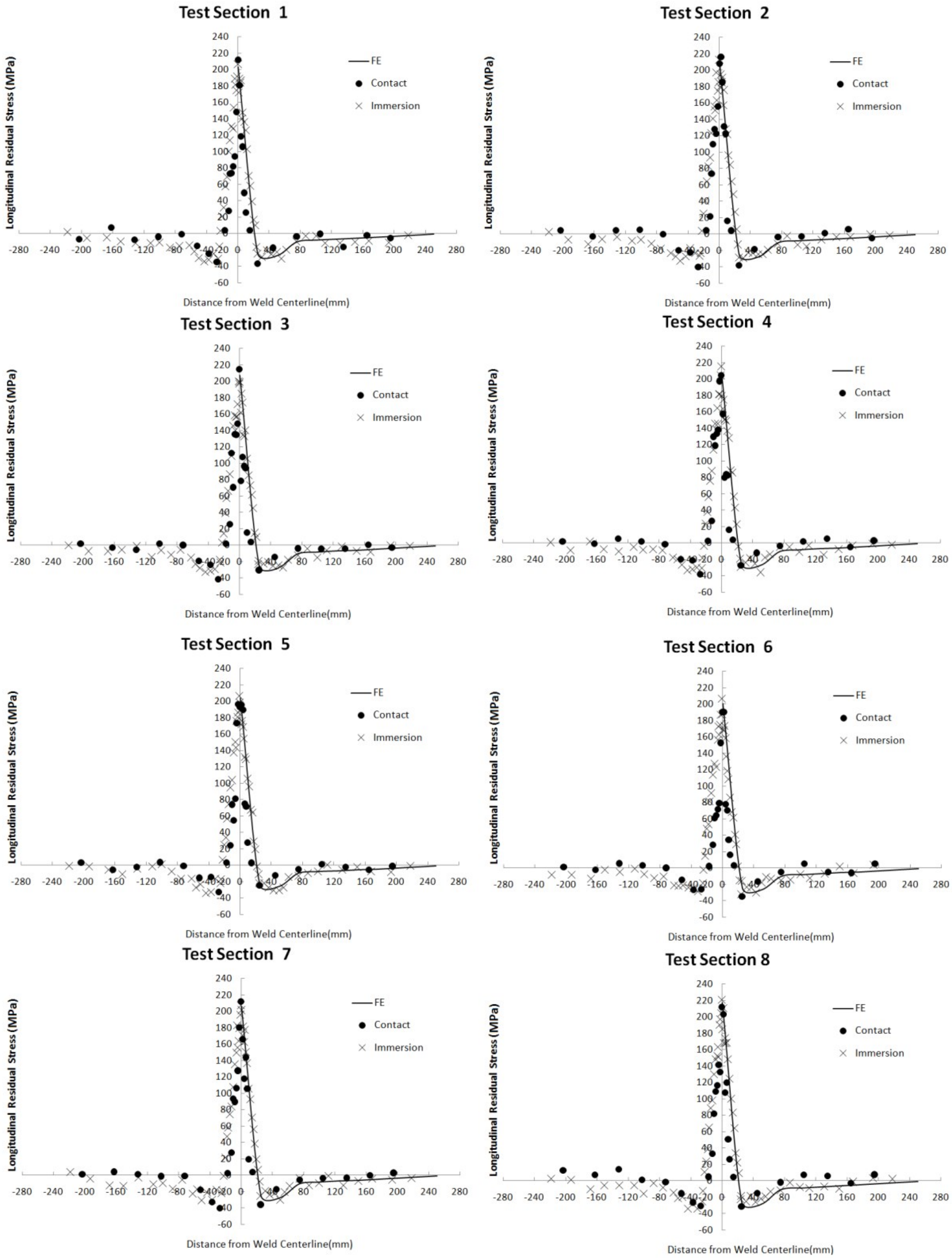

Fig.14. Comparison of FE with Contact and Immersion Ultrasonic Results according to the Test Section