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Investigation of Total Welding Residual Stress by Using Ultrasonic Wave Velocity Variations

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ABSTRACT

Objective of this study is prediction of residual stress in three pass welded stainless steel plates. In this approach residual stress through the thickness of the material is measured. Two 316L stainless steel plates are manufactured as the same samples. Three weld passes are applied to one of these samples. Other is zero stress state reference sample. According to the principle that Ultrasonic wave speed is constant for a material these waves are used to detect variations in the crystal structure of materials. The source of welding residual stress is welding heat. The relation between thermal stress and ultrasonic wave velocity variations are investigated. By using this relation and ultrasonic wave velocity changes between two samples, residual stress distribution throughout the welded sample is determined. 2D residual stress distribution data brought information that residual stress through the thickness of the material is high around weld beam. When compared to the previous studies on residual stress measurement, the residual stress through the thickness of the material is measured except surface residual stress. In addition, this study provides a practical approach for residual stress measurement.

***Key Words*: :** *Ultrasonic technique, Residual stress, Welding, Thermal stress*

1. INTRODUCTION

Over the last few decades, various residual stress measurement techniques have been developed. In general, these techniques are qualified as destructive and non-destructive techniques. Destructive methods measure by destroying the state of equilibrium of the residual stress and measure only the consequences of stress relaxation occurred by destruction. Most common destructive techniques are the hole drilling method, the ring core technique, the bending deflection method, and the sectioning method. These methods are widely used in industry and they are sensitive to the macroscopic residual stress. Non-destructive methods are developed on the basis of the relationship between residual stress and the physical or crystallographic parameters. Different non-destructive techniques are developed such as the X-ray diffraction method, the neutron method, the ultrasonic method, and the magnetic method. Furthermore, related to the development of computer technologies, numerical modeling methods such as finite element method have an important role on prediction of residual stress [1].

Thermal stresses are formed as a result of thermal processes, such as welding. These thermal processes cause non-uniform temperature changes in material. Associated with local heating, expansion and contraction occur around the heated zone of the material. However, expansion zone is surrounded by the

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material that has not been heated and this part prevents material to expand or contract freely and residual stresses are formed. The basic relation that expresses thermal stress is given in Equation 1;

$$\sigma = E\,\alpha_L\,\Delta T \tag{1}$$

where σ is the thermal stress, E is the modulus of elasticity, α_L is thermal expansion coefficient, and ΔT is temperature change. By observing the relation between thermal stresses and ultrasonic wave velocity, it is possible to determine thermal residual stresses in a welded material.

By using ultrasonic method it is possible to measure surface stresses and through-thickness volume stresses. Basic principle of ultrasonic technique is detecting variations of ultrasonic wave speed and relating them with crystallographic parameters. In the previous studies surface stresses are measured by the critically refracted longitudinal wave [2, 3] and pulse echo methods [4, 5]. In these studies relation between ultrasonic wave velocity and stress are accomplished by using mechanically determined acoustoelastic constants [6]. In this study, the relation between thermal stress and ultrasonic wave velocity is investigated. The variation in the wave velocity is related with the sum of the principal stresses [6, 7]. Ultrasonic velocity distribution through the thickness was measured in unwelded and welded samples. Variations of velocity caused by welding residual stress are calculated. Finally, the relation between ultrasonic wave velocity and thermal stress is used to calculate residual stresses.

2. EXPERIMENTAL STUDY

Residual stress measurement by ultrasonic method is based on acoustoelastic effect. Different experimental configurations are composed of determining acoustoelastic constant and measurement of wave velocity variations [7-16]. Applications are varied on among different type of materials such as steel plates, rail steel, steel cylinders, and other type of metals. This study represents a technique based on an acoustoelastic constant that is determined according to thermal stress. In addition a reference unwelded sample is used to determine zero stress state. Measurements are performed throughout the plates on selected coordinates. Wave velocity variations on the same coordinates are observed to calculate residual stress distribution.

Experimental studies are performed by using computer integrated ultrasonic precision thickness gauge system with 0.1 % sensitivity and measurements are performed by using the transducer as illustrated in Figure 1. Transducer diameter is 8 mm and coupling material to transfer wave from probe to the steel plate is silicon oil. This system is capable of sensitive thickness measurement of materials and computer integration allows investigation of wave distribution throughout the material. In this study this system is used to measure ultrasonic wave velocity.

Table 1. Constants for 316L austenitic stainless steel

Modulus of Elasticity	193 GPa
Thermal Expansion Coefficient	15.9 $^{o}C^{-1}$

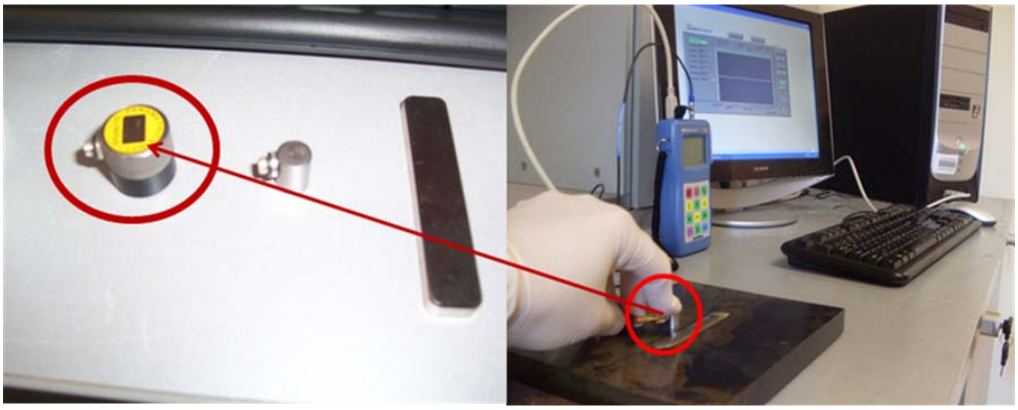

Figure 1. Experimental setup

The steel plate was provided by British Energy [17]. Type of the steel is 316L and literally determined properties are given in Table 1. Pictures of the welded and unwelded samples with measurement directions are given in Figure 2. Results are also given in accordance with these directions.

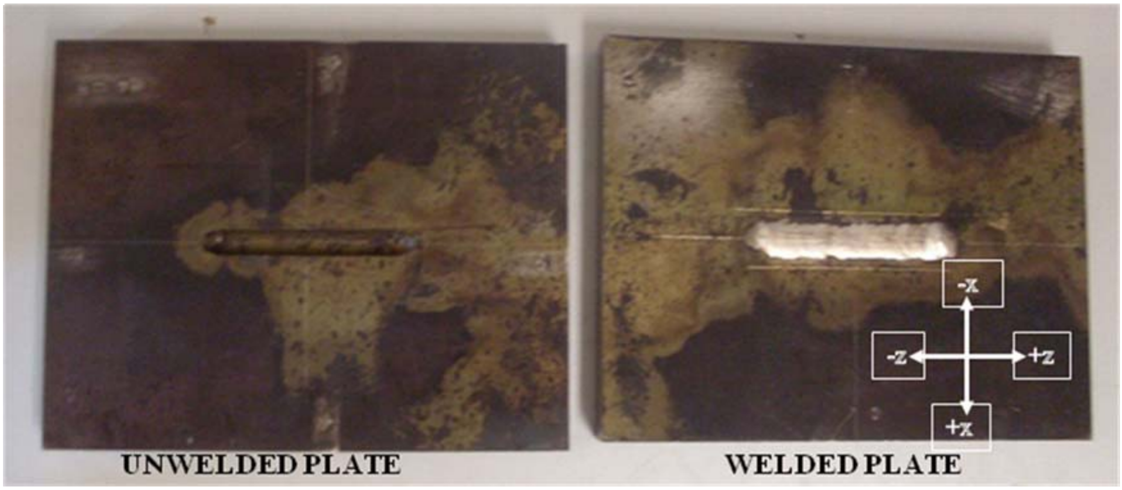

Figure 2. Images of welded and unwelded sample

Ultrasonic wave velocity measurements are performed on unwelded and welded plates. Through thickness wave velocities are measured from 13 X 16 predetermined points. Measurements are repeated 5 times and standard deviation at each measurement set is determined.

Unwelded reference plate is heated in order to investigate relation between the thermal stress and ultrasonic wave velocity. Whole plate is heated up until the steady state condition is achieved and ultrasonic wave velocity is measured. Measurements are repeated for increasing temperature from 26 ^oC to 65 ^oC. Thermal stresses are calculated by using Equation 1. Initially there are no velocity and temperature change. Relation between $\Delta V/V_0$ and thermal stress are plotted in Figure 3.

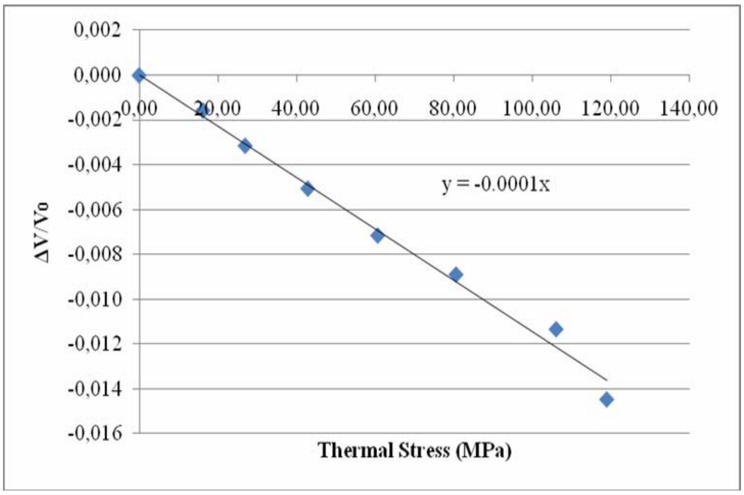

Figure 2.3. Relation between wave velocity change and thermal stress

There is a linear relation between $\Delta V/V_0$ and thermal stress. Best fitting line states that thermal stress is 0.0001 times of $\Delta V/V_0$. This ratio brings thermally determined acoustoelastic constant as $K = 0.0001$ Mpa^{-1}. Consequently, thermally induced residual stresses can be calculated by using this linear relationship given by Equation 2;

$$\sigma = \frac{1}{K}\frac{V - V_0}{V_0} \qquad (2)$$

where σ is the thermal stress, K is the thermally determined acoustoelastic constant, V_0 is the initial wave velocity, and V the wave velocity after welding.

3. RESULTS AND DISCUSSION

Results of ultrasonic wave velocity measurements of unwelded and welded samples are given in Figures 4 and 5. Wave velocities increase from light blue to dark red as represented in the color scale. Marked zone indicates the weld zone.

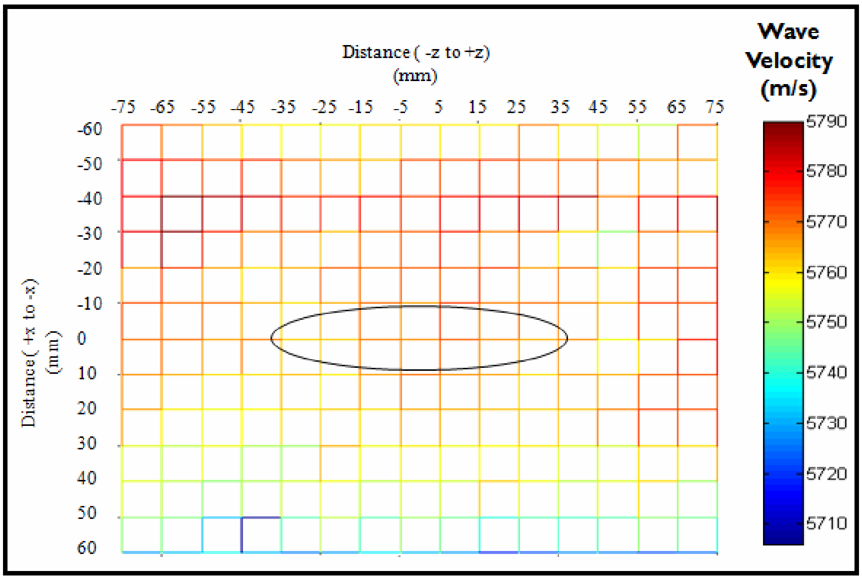

Figure 4. Ultrasonic wave velocity distribution in unwelded sample

Results state that wave velocity decreases from –x direction to +x direction. Both of the plates show the same velocity changes because these two samples have same material characteristics.

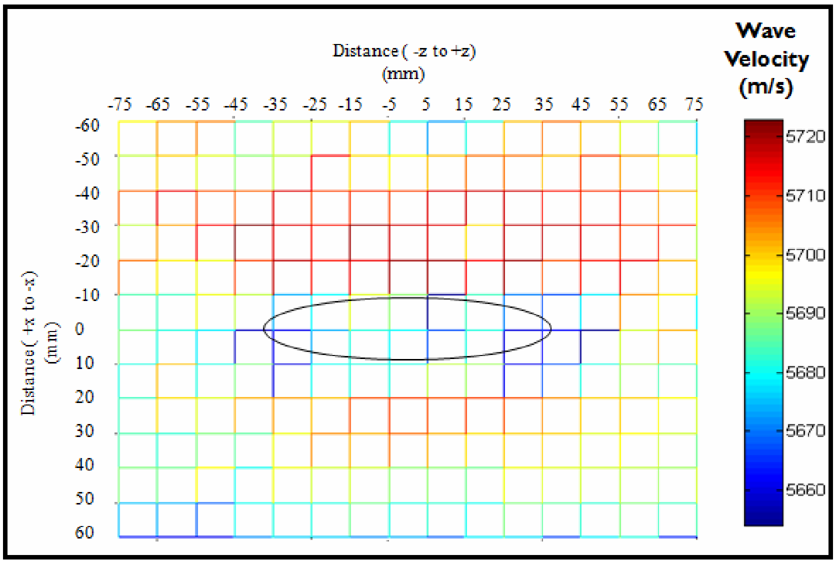

Figure 5. Ultrasonic wave velocity distribution in welded sample

The differences between unwelded and welded sample wave velocities are calculated by subtracting wave velocity of unwelded sample from welded sample. Results are plotted in Figure 6. Wave velocity variations are different at each coordinate of the sample. Blue zone is darker around weld beam. In that zone velocity change is higher. As a result of welding process this zone is exposed to high amount of heat and rapid cooling. This process caused formation of residual stress. Stresses in material affect wave velocity in the material. When the total stress in the material increases, wave velocity decreases linearly as it is stated in chapter 2. Velocity change is observed all over the material. However, welding heat mostly affected heat affected zone and velocity decrease is higher in this zone.

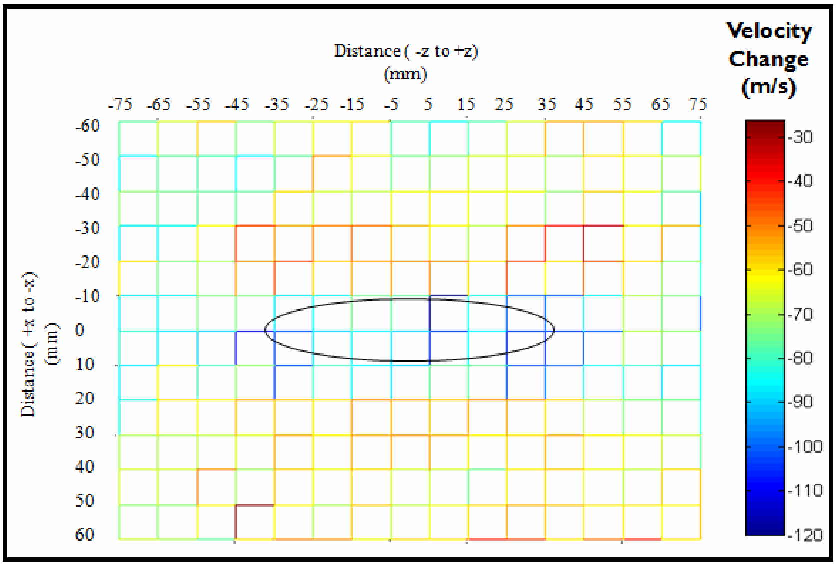

Figure 6. Ultrasonic wave velocity change after welding process

Results of residual stress calculations are given in Figure 6. Dark red represents the zone with high residual stress. Residual stress increases around the weld zone. These are the total stresses as sum of longitudinal, transversal, and vertical stresses at each measurement point. Residual stress distributions on selected points along weld start to weld end through the transversal direction are also given in Figure 8. Total residual stress increases around weld zone. In the weld start and end points total residual stress is higher than center of the weld.

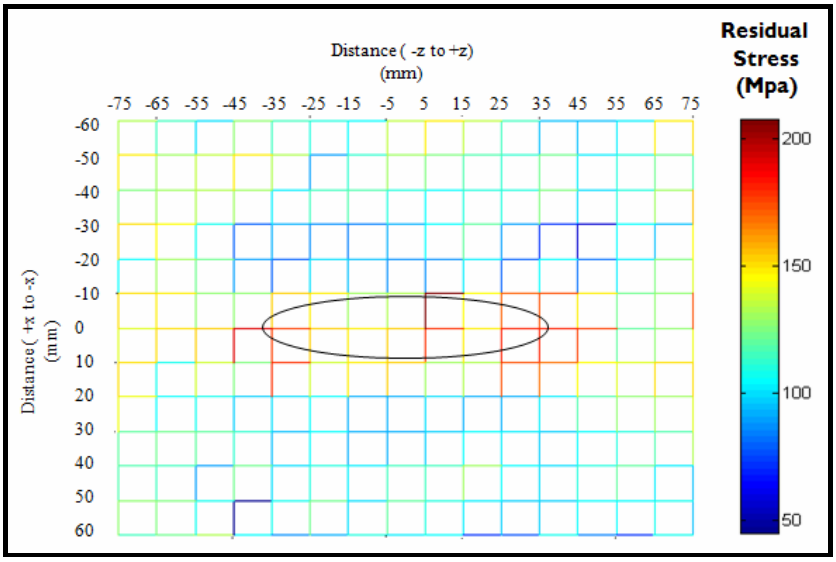

Figure 7. Total residual stress distribution throughout the welded plate

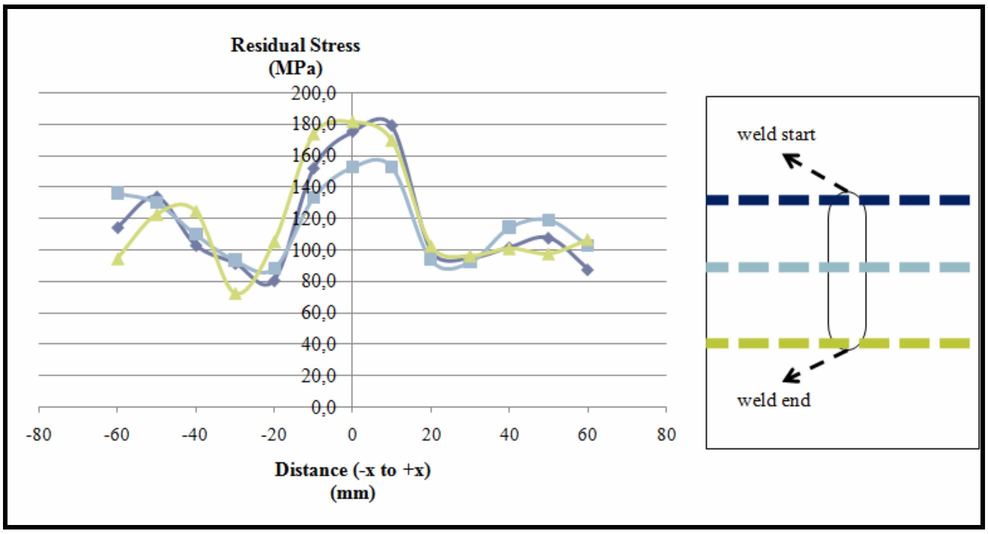

Figure 8. Total residual stress distribution through the transversal direction

In this study, the relation between thermal stress and ultrasonic wave velocity is investigated. By using this relation, thermal residual stresses are calculated. Result of the thermal test states that ultrasonic wave velocity change and stress have a linear relationship.

Wave velocity distributions are similar except the welded zone and there is a decrease in wave velocity from –x to +x direction in both samples. In terms of this data it can be stated that these two plates have the same characteristics.

Ultrasonic wave velocities are higher in the unwelded plate and decreases in the welded plate. The difference between welded and unwelded samples is higher around the weld zone. Residual stresses at each point are calculated by using the relation between ultrasonic wave velocity change and thermal stress. These are total residual stresses through the thickness of the material.

As it is expected residual stresses are higher around weld zone. Most of the studies on residual stress state zero residual stress away from weld zone. However, these studies mostly dealt with surface residual stresses. They do not give information about inner residual stresses. In this study residual stresses are total residual stresses through the thickness. Residual stresses are formed throughout the plate and minimized away from the weld zone in the transversal direction.

Most of the previous studies based on ultrasonic waves are focused on surface residual stresses. Different residual stress measurement methods such as X-Ray diffraction method or hole drilling method and other methods deal with surface stresses. In this study bulk residual stress is calculated as total residual stresses through the thickness of the material. When compared to previous studies this study represents similar distribution of residual stress. However, in this study residual stresses are observed all over the material. Because this method measures total residual stresses in three axes. On the other hand, surface methods measure only surface residual stresses in one direction and these stresses can be observed only around the weld beam.

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