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Nondestructive Evaluation of Welding Residual Stresses in Austenitic Stainless Steel Plates

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ABSTRACT

This paper investigates the nondestructive capability of ultrasonic waves in residual stress evaluation of austenitic stainless steel plates (AISI 304L). Longitudinal critically refracted (L_{CR}) waves are employed to measure the residual stresses. Measuring the acoustoelastic constant through the tensile test is eliminated on the main investigated sample to keep it intact. Another welded plate with the same welding specification, geometry, thickness and the same material is used to extract tensile test samples. To find the acoustoelastic constant of the heat affected zone (HAZ), a metallographic investigation is done to produce microstructure similar to that of the

HAZ in a tensile test sample. A finite element model of welding process, which is validated by hole-drilling method, is used to verify the ultrasonic results. The results show good agreement between finite element and ultrasonic stress measurements which is accomplished nondestructively.

Keywords: Finite Element Welding Simulation; Ultrasonic; Nondestructive Stress Measurement; L_{CR} waves; Acoustoelastic Constant.

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 stress. 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 [1] that sensitivity of the L_{CR} waves to the strain is highest between the other types of ultrasonic waves. They measured the strain sensitivity of different ultrasonic waves including longitudinal wave propagated parallel to the stress direction, longitudinal wave propagated perpendicular to the stress direction, transversal wave parallel and perpendicular to the stress direction and also polarized in different directions. They found that the longitudinal ultrasonic waves propagated parallel to the stress direction show the most strain sensitivity while their characterizations is same as the L_{CR} waves. Tanala et al. [2] determined acoustoelastic constant of 316L stainless steel and 5086 aluminium. They investigated welded stainless steel pipe and aluminium plates to measure residual stress distribution by employing subsurface longitudinal waves. The results of ultrasonic stress measurements were compared with those obtained from the X-ray diffraction technique. They reported high potential of ultrasonic waves in residual stress measurement of aluminium and stainless steel alloys. Walaszek et al. [3] measured the acoustoelastic constant directly in the weld by preparing a tensile test sample from the melted zone in the P460 and P265 steel. Their work was among the initial studies considered to the microstructure effects on the L_{CR} waves. They concluded that neglecting the microstructure effects would lead to overestimation of stress distribution which is not recommended. Lu et al. [4] 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. However they did not experimentally measure the stresses on the weld zone. Palanichamy et al. [5] measured the residual stresses in austenitic stainless steel weld joints using ultrasonic technique. They employed the L_{CR} waves to measure subsurface residual stresses caused by activated tungsten inert gas (ATIG) welding process and compare the results with those obtained from the tungsten inert gas (TIG) process. Before the micro-structural investigation by Qozam et al. [6], the residual stresses evaluation in the steel welded plates, by the use of the L_{CR} wave method, was only possible in the melted zone (MZ) and in the parent material (PM). While in the HAZ, the residual stresses were incorrectly evaluated due to its small width impeding the extraction of the calibration sample. They proposed reproducing the microstructure of this zone using a specific heat treatment to solve the problem. Their technique is also used in this study to reproduce HAZ microstructure in a tensile test sample extracted from stainless steel plate.

In all of the previous studies, the ultrasonic stress measurement was used and considered as a nondestructive method while the tested materials were cut and machined to extract the tensile test specimens for measuring the acoustoelastic constant. This practical problem in ultrasonic stress measurement confines it to only lab applications. Some studies claims that the acoustoelastic constant measurement is not necessary by using a complete table of acoustoelastic constant for all of the materials. Today, this claim is under question because it is approved, in many of above reviewed studies, the acoustoelastic constant of the weld zone differs considerably from the parent material and the HAZ as well. It means that the welding procedure specifications (WPS) have a severe effect on the acoustoelastic constant. Therefore, it is impractical to make a complete table of acoustoelastic constants for each combination of material, dimensions and welding specifications. One way to solve the problem is preparing a smaller model of original welded construction with exactly the same WPS, thickness and material. The prepared model can be used to extract tensile test samples and to calculate the acoustoelastic constant. The calculated constant can be employed to relate the measured time of flight of ultrasonic wave in the main structure to the stress, based on the acoustoelasticity relations. In this study a comparison is made between the values of stresses calculated by the proposed method and those obtained from finite element analysis. The finite element welding simulation, which is validated by hole-drilling method, is used here to verify the ultrasonic stress measurements.

2- THEORETICAL BACKGROUND

2-1. L_{CR} method

The L_{CR} method uses a special longitudinal bulk wave mode, as shown in Fig.1, mainly propagating beneath the surface at a certain depth. When a longitudinal wave passes through an interface between two materials, there is an incident angle that makes the angle of refraction for the wave 90°. This is known as the first critical angle which is calculated 28° from the Snell's law when the wave moves from PMMA wedge to the steel.

A simple form for the relation between measured travel-time change of L_{CR} wave and the corresponding uniaxial stress is expressed as the following equation:

$$\Delta\sigma = \frac{E}{L_{11} t_0}(t - t_0) \qquad (1)$$

In equation (1), σ is stress, E is the elastic modulus and L_{11} is the acoustoelastic constant for longitudinal waves propagating in the direction of the applied stress field. The index "11" refers to the longitudinal wave propagated parallel to the stress direction while L_{11} is the corresponding acoustoelastic constant. Also, t is the experimental flight-time which would be measured on the welded structure that is being evaluated; t_0 is flight-time for a homogeneous, isotropic, stress-free sample at the room temperature. For a fixed probe distance, the travel time of the L_{CR} wave decreases in compressive stress and increases in tensile stress field. With knowledge of the weld induced change in flight-time along with the measured acoustoelastic constant, the welding residual stress would be calculated.

Equation (1) could be changed into equation (2) to be used in calculation of the acoustoelastic constant (L_{11}):

$$L_{11} = \frac{E}{\sigma \times t_0}(t - t_0) \qquad (2)$$

A uniaxial tensile test is needed to measure the parameters of equation (2). A tensile test specimen is extracted from the work piece and would be exposed to the tensile test while the ultrasonic transducers are assembled on the specimen to measure flight-time (t) of the L_{CR} wave. However, the tensile test specimen should be stress relieved before starting the tensile test to measure the flight-time of free stress sample (t_0). By using a tensile test machine, the tensile test (σ) is increased step by step while the flight-time (t) is measured in each step. The elastic modulus (E) could also be measured by using the tensile test results or obtaining from the material tables. As a result, the acoustoelastic constant (L_{11}) can be calculated. In this study, the tensile test specimens are extracted from the MZ, HAZ and PM to measure the E and L_{11} in all of these zones separately.

2-2. Finite Element Welding Simulation

Earlier studies of welding simulation by Finite Element (FE) accounted for the nonlinearities because of temperature dependent material properties and plastic deformations [7]. The majority of those studies, due to weakness in the computational capabilities of the previous computers, were limited to two-dimensions on the plane perpendicular to the welding direction. However, good agreements have been observed between the numerical predictions and experimental results which encourage using FE welding simulation in residual stress evaluation [8, 9].

Numerical simulation of the welding residual stresses needs, to take account of the mechanical behaviour of welds, which is sensitive to the close coupling between heat transfer, microstructure evolution and thermal stress analysis. The phenomena involved in the heat input such as arc, material interactions, as well as, fluid dynamics in the weld pool are not precisely described. From the thermo-mechanical point of view, the heat input can be seen as a volumetric or surfaced energy distribution, and the fluid flow effect, which leads to homogenise the temperature in the molten area, can be simply taken into account by increasing the thermal conductivity over the melting temperature. As no metallurgical transformation occurs in the austenitic stainless steel (304L), the detailed modelling of the melting 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. Material modelling has always been a serious issue in the simulation of welding because of the scarcity of material data at elevated temperatures. The material properties of 304L stainless used in the finite element analysis is extracted from X.K.Zhu et al [11].

The problem is formulated as a successively coupled thermal stress analysis. First, a nonlinear 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 nonlinear 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. A full Newton-Raphson iterative solution technique with direct sparse matrix solver is employed for obtaining a solution. 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 nonlinear 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 plates is shown in Fig.2.

3- EXPERIMENTAL PROCEDURES

3-1. Sample Description (Plate 1&2)

Two welded plates (Plate 1 and Plate 2) with 10 mm thickness are prepared from austenitic stainless steel (Table 1). The plates are stress relieved by a heat treatment process (heating at 450° C for 6 hours following furnace cooling) to eliminate residual stress produced in the preliminarily manufacturing processes. After the stress relieving process, single pass butt-weld joint geometry with a back-weld pass, without root gap and with V-groove (90° included angle) is used for both of the plates. Back and the main weld passes are performed by submerged arc welding (SAW) process with the specifications mentioned in Table 2. The experimental efforts to produce similar welds in both of the plates include simultaneous machining of them to create the groove angle, using zero gaps and employing the new calibrated automatic SAW machine. The metallographic inspection of the welds shows similar weld and HAZ dimensions related to the Plate 1 and Plate 2 (Fig. 3) which confirms satisfying results of the experimental efforts to produce similar welds.

3-2. Measurement device for TOF measurement on the Plate 2

The contact measurement device, shown in Fig.4, includes an ultrasonic box, computer and time of flight (TOF) measuring element. 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 1ns. TOF measuring element includes three normal transducers assembled on an integrated wedge to measure the time of flight. A poly methyl methacrylate (PMMA) material, under the trademark Plexiglas, was cut by laser cutting to construct the wedge. A three-probe arrangement was used, with one sender and two receivers in order to eliminate environment temperature effect to the travel time. Three normal transducers with the same frequency were used where their nominal frequencies were 2 MHz and the diameter of the piezoelectric elements was 6 mm. The measurement devices are used to measure TOF on the Plate 2 and these data along with measured acoustoelastic constant of Plate 1 will be used to calculate residual stresses of Plate 2 based on equation (1).

3-3. Determination of L_{CR} Penetration 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. However, there is no definite relation between L_{CR} depth and frequency. Hence, depth which the L_{CR} wave could penetrate should be measured experimentally. A variable depth groove is cut in a plate, with the same material and thickness of the tested plates, to produce a barrier to physically prevent the L_{CR} wave from reaching the receiver transducer. It was found that a 2 mm depth groove could completely prevent a 2 MHz L_{CR} wave to pass, which indicates that the penetration depth of such a L_{CR} wave is 2 mm.

3-4. Acoustoelastic constant evaluation of the Plate 1

To evaluate the acoustoelastic constant (L_{11}), the tensile test samples were taken from both sides of the Plate 1. Rectangular tensile test specimens were extracted from parent material (PM), melted zone (MZ) and heat affected zone (HAZ) separately. Metallographic analysis of the weld shows that the heat affected zone (HAZ) is not large enough to extract tensile test sample (Fig.3). Therefore, samples were prepared from tensile test specimens, extracted from the parent material, to reproduce microstructure of HAZ by means of heat treatment. Each sample has experienced different annealing temperature, annealing time, cooling rate and cooling environment. Since no microstructure phase change occurred in the HAZ during the welding process, the austenite grain size in the microstructure of the sample was considered as a criterion in the reproduction of HAZ microstructure. From this point, the best agreement was found for the sample annealed at 1200°C for 7 min followed by an air cooling (Fig.5). The grain size of HAZ and simulated sample were close to the G5.5 according to the ASTM-E112 (standard test methods for determining average grain size).

3-5. Hole-drilling and metallographic investigation to validate FE model

The FE welding simulation is employed to verify the ultrasonic stress measurement results. However, the FE model is also needed to be verified by using the other experimental methods. A metallographic investigation is accomplished to measure the weld and HAZ dimensions (Fig.3). Comparing the measurements with those obtained from the thermal analysis of FE simulation, would be a proper verification of FE model. Furthermore, the mechanical analysis of FE simulation is validated by utilizing the hole-drilling measurement of longitudinal residual stresses. The hole-drilling method is performed in four different points based on the characterizations described in ASTM: E837.

3-6. Nondestructive evaluation of welding residual stresses

The following steps should be accomplished to evaluate longitudinal residual stresses nondestructively on the Plate 2:

1- The measurement devices (section 3-2) are employed to measure TOF on the Plate 2 related to the MZ, HAZ and PM zone separately. However, the TOF measurement is performed parallel to the weld direction (Fig.4.) which leads to longitudinal stress measurement.

2- Tensile test specimens are extracted from MZ and PM zone while some of PM specimens have experienced a pre-determined heat treatment process to be converted to the HAZ samples.

3- The value t_0 is measured directly on the stress-free samples which are the tensile test specimens extracted from MZ, HAZ and PM zone. The stress-free situation is created by employing stress relieving heat treatment.

4- The elastic modulus (E) is measured by using tensile test on the specimens extracted from MZ, HAZ and PM zone.

5- The acoustoelastic constant is measured on Plate 1 by using a uniaxial tensile test (section 3-4) and equation (2) in the MZ, HAZ and PM zone separately.

6- By assuming the same acoustoelastic constant of Plate 1&2 and putting the results of step 1-5 in equation (1), longitudinal residual stresses can be calculated for the Plate 2 while no destructive process has been performed on it.

Comparing the ultrasonic stress measurement results with those obtained from FE simulation could lead to nondestructive measurement of welding residual stresses while the mentioned steps are summarized in Fig.6.

4- RESULTS AND DISCUSSION

The results of tensile test are shown in Fig.7 where the slope of the lines represents L_{11} acoustoelastic constant. All the measured data are related to the Plate 1 and will be used in equation (1) to calculate residual stresses of Plate 2. The L_{11} constant is measured 1.839, 2.102

and 2.452 in the HAZ, PM and MZ respectively which show that the HAZ constant is less than the PM whereas the maximum is the MZ constant. This relationship between the MZ, HAZ and PM acoustoelastic constant was previously reported by Qozam et al. [6].

Using the MZ constant for the stress calculation of the HAZ is proposed in some of the previous studies because of practical limitations of constant measurement in the HAZ. There are % 25 differences between the acoustoelastic constant of the HAZ and MZ according to the Fig.7, therefore ignoring the constant measurement of the HAZ is not recommended. Neglecting the HAZ acoustoelastic constant measurement was also discommended in previous studies [3, 6, 14-17].

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. The wave speed for L_{CR} waves is affected by the average stress in a layer that may be a few millimetres thick [14-17] which means that ultrasonic method measures the average of stresses in determined depth. For example, the 2 MHz L_{CR} wave travels in 2 mm from the surface and give the average of residual stress in this zone. Therefore, 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 used to compare with those obtained from ultrasonic measurements.

For further verification of FE model, hole-drilling test is performed in 4 different points on the Plate 2 according to the Fig.8. The average results of FE residual stress in 2 mm from the surface 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 FE results are in good agreement with welding logic, which says "The maximum of tensile residual stress is produced in the weld centreline and it will be transformed to compressive stress near the HAZ and finally free stress zone in the parent material" [10, 16, 17].

In the ultrasonic method, measured TOF of Plate 2 and measured acoustoelastic constant of Plate 1 are put in equation (1) to calculate the residual stresses. The results obtained from FE model and ultrasonic measurements are compared in Fig.9. The results of ultrasonic measurements show an acceptable agreement with finite element analysis in Plate 2. The deviation is less than ±16 MPa, which is about % 8 of yield strength according to the tested material. However, the acoustoelastic constant of Plate 1 is used in stress calculation of Plate 2, while there is not any destructive process performed on the Plate 2.

5- CONCLUSION

The main goal of this paper is to investigate the capability of L_{CR} ultrasonic method in residual stress measurement in stainless steels welded plates. Finite element model, hole-drilling and ultrasonic stress measurements methods are employed to two welded plates with the same material, thickness and WPS. The acoustoelastic constant is measured on the Plate 1 while the Plate 2 is kept intact to be measured in terms of ultrasonic wave TOF. According to the achieved results, it can be concluded that:

1) The FE results are in good agreement with welding logic, which says "The maximum of tensile residual stress is produced in the weld centreline and it will be transformed to compressive stress near the HAZ and finally free stress zone in the parent material".
2) The average results of FE residual stress in 2 mm from the surface are in good agreement with those of hole-drilling method in the Plate 2.

3) The acoustoelastic constant of HAZ is less than the PM while the MZ constant is the maximum.
4) There are % 25 differences between the acoustoelastic constant of the HAZ and MZ, therefore ignoring the constant measurement of the HAZ is not recommended.
5) The measured residual stresses of the Plate 2 are in good agreement with those predicted by the FE analysis while the acoustoelastic constant of Plate 1 is used in the calculation of residual stresses.
6) The deviation between the ultrasonic measurements with the FE results is less than ±16MPa, which is about % 8 of yield strength according to the tested material.

The Plate1 is a prepared model from Plate 2 to eliminate the destructive machining process for measurement of acoustoelastic constant. The model preparation can be used in the industrial application to measure the residual stresses nondestructively. However, a little change in the material, joint geometry, thickness and welding specifications can influence on the acoustoelastic constant of the weld zone or HAZ and is not recommended in model preparation. Since the Plate 2 has experienced no destructive process and is completely intact, the proposed method can nondestructively evaluate the welding residual stresses of the austenitic stainless steel plate.

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7- LIST OF FIGURE CAPTIONS

Fig. 1. Three transducers configuration to produce the L_{CR} wave

Fig. 2. Basic FE model

Fig. 3. Weld and HAZ dimensions in Plate1 and Plate 2

Fig. 4. TOF Measurement Devices on the Plate 2

Fig. 5. Microstructure of a) HAZ and b) Simulated Sample to reproduce HAZ microstructure (Electro-etched with 10 % Oxalic acid for 2 min at 200 X)

Fig. 6. Flowchart of Nondestructive stress evaluation

Fig. 7. Tensile test Results (Slope of the lines represents L_{11} acoustoelastic constant of the Plate 1)

Fig. 8. The Comparison of Finite Element and Hole-drilling Method

Fig. 9. Comparison of FE with Ultrasonic Results of Plate 2

8- TABLES CAPTION

Table 1: Dimensions and chemical compositions of Plate 1 and Plate 2

Table 2: Welding specifications of Plate 1 and Plate 2