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Comparison between using longitudinal and shear waves in ultrasonic stress measurement to investigate the effect of post-weld heat-treatment on welding residual stresses

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ABSTRACT

Fusion welding is a joining process widely used in the industry however, undesired residual stresses are produced once the welding process is completed. Post-weld heat-treatment (PWHT) is extensively employed in order to relieve the welding residual stresses. In this study, effect of PWHT time and temperature on the residual stresses of a ferritic stainless steel is investigated. Residual stress distributions in eight welded specimens were measured by using an ultrasonic method. Ultrasonic stress measurement is a non-destructive method based on acoustoelasticity law, which correlates mechanical stresses with velocity of an ultrasonic wave propagating within the subject material. The ultrasonic wave employed could be longitudinal or shear wave produced by the longitudinal (normal) or transverse (shear) transducers, respectively. Ultrasonic stress measurements based on longitudinal waves use longitudinal critically refracted (L_{CR}) waves in this direction, while shear wave methods use an ultrasonic birefringence phenomenon. The results show that the effect of PWHT can be successfully inferred by both longitudinal and shear wave methods, but the former is found to be more sensitive to stress variation. Furthermore, the distribution of sub-surface residual stresses is found to be more distinguishable when the L_{CR} method is employed.

Keywords: Post-Weld Heat-Treatment; Ultrasonic Stress Measurement; Welding Residual Stress; Acoustoelasticity; Ultrasonic Longitudinal Wave; Ultrasonic Shear Wave.

1- INTRODUCTION

Fusion welding changes material properties, causes deformation and imparts residual stress into components. Welding involves melting and subsequent cooling along the welding path, which is a cause of residual stress development. During welding processes, the yield stress and elastic modulus decrease through increased temperature, while thermal stress is introduced in regions outside of the weld area. Some thermal stresses can be accommodated by local plastic deformation. Non-uniform and localized plastic deformation will form residual stresses within the component to reach static equilibrium upon cooling. The magnitude and distribution of residual stresses is dependent on various parameters such as material properties, clamping arrangement, component thickness, preheating temperatures and welding parameters [1]. Residual stresses developed during welding could be a source of complication for further manufacturing steps and undermine performance and curtail the operational life of the welded structure. These problems can arise immediately after the welding process or during the operational life of the welded equipment. For the majority of industries (aerospace, marine, petrochemical, etc.), a high amount of residual stress are unacceptable because of accelerated failure mechanisms such as fatigue or stress-corrosion-cracking (SCC) with the latter a common failure mechanism in ferritic stainless steels [2].

Post-weld heat-treatment (PWHT) is generally used as a supplementary fabrication process of welded structures in order to reduce welding residual stresses. PWHT can change the microstructure and mechanical properties of the material [2]. The order of changes in material properties and amount of residual stress is strongly depended on PWHT conditions. Time, temperature and cooling rate are considered the most effective parameters in PWHT. In stress relieving by using PWHT, the temperature should be made high enough to temper both weld-metal and heat-affected-zone (HAZ). In ferritic stainless steels, this leads to enhance corrosion resistance accompanied by a decreased tendency for stress corrosion cracking (SCC). For ferritic stainless steel, the usual annealing temperature range is approximately 700-820 °C. The annealing time and temperature depends on the structure's thickness and could vary from few minutes (for thin sheet) to several hours (for heavy plate). The cooling process of the ferritic stainless steels from the annealing temperature can be carried out in air or water, however parts are permitted to be cooled in a furnace to about 600 °C followed by rapid cooling in either medium. A slow cooling rate through the temperature range of 570 °C down to 400 °C should be avoided because it induces room temperature brittleness [3-4].

Residual stress measurement is often a necessary process in quantifying the reliability of mechanical equipment. Several methods are accessible for stress measurement including three main categories: destructive, semi-destructive and non-destructive methods [5]. Destructive and semi-destructive techniques, also known as mechanical or relaxation based methods, are based on measuring elastic deformation produced upon relieving residual stress by removing material from a component. Slitting and the contour method are principal destructive techniques in which the specimen is completely destroyed in order to evaluate residual stresses. Hole-drilling, ring-core and deep-hole-drilling are examples of the semi-destructive techniques leaving small holes on the material surface. ASTM: E837 has standardized the hole-drilling method and is now considered a reliable method and is often used to verify other residual stress measurement methods [6-8]. Non-destructive measurement of residual stress is often required since numerous structures need to be inspected periodically to avoid major damage and failure. Non-destructive methods usually measure waveform propagation or transmission through the component, which are indirectly affected by residual stress.

One of the more easily accessible methods for non-destructive residual stress measurements is the use of ultrasonic waves. Ultrasonic stress measurement is founded on the linear relation between velocity of the ultrasonic wave and built-in elastic stress fields. This relationship is known as the acoustoelastic effect [9].

In 1958, the birefringent phenomenon of acoustic waves was discovered by Bergman and Shahbender [10] and developed by Benson and Raelson [11]. In a uniaxial tensile test on a metallic specimen, changing the amount of stress was found to have different effects on the velocity of a shear wave polarized along the axis of applied stress compared with the velocity of the wave polarized perpendicular to this same axis. In 1967, Crecraft [12] showed that acoustoelastic behavior along with the ultrasonic birefringence effect could be employed for non-destructive stress measurement on metals.

It was shown by Egle and Bray [13] that the sensitivity to stress of longitudinal waves propagated parallel to the stress direction is highest compared to other directions. In 1994, Schneider et al [14] presented an experimental setup for ultrasonic stress measurement by employing longitudinal waves. Bray and Tang [15] used longitudinal critically refracted (L_{CR}) waves to evaluate bending stress in steel plates and bars. They employed longitudinal ultrasonic probes actuating by different testing frequencies (2.25 MHz and 5 MHz) and compared the results. They confirmed a unique capability of the L_{CR} method, which is penetrating into different depths of the material (by changing the testing frequency of ultrasonic probes) and measuring sub-surface stresses at different depths. This ultrasonic capability for sub-surface stress measurement was also later confirmed by Javadi et al. [16-17].

Recently, employing L_{CR} waves has found higher uptake in the ultrasonic stress measurement community and the recent studies favor the use of longitudinal versus ultrasonic shear waves [18-33]. However, a comparison between using the L_{CR} and shear waves for ultrasonic stress measurement has not been thoroughly investigated in previous studies. Hence, residual stresses imparted during welding are measured in this study using the L_{CR} method and the results are compared with the results of a shear wave method. The two methods will be discussed in terms of sensitivity and flexibility as they apply to measuring the effectiveness of a PWHT performed on ferritic stainless steel plates. This effect is also investigated on distribution of subsurface residual stresses, which are characterized differently by either L_{CR} or shear waves.

2- THEORETICAL BACKGROUND

2.1. Ultrasonic stress measurement using L_{CR} waves

While there are many experimental setups which can be used for residual stress measurements with L_{CR} waves, a common configuration is to employ three ultrasonic transducers with the same actuating frequency. A longitudinal wave is created at the first critical angle by a transmitting (sender) transducer and then propagated parallel to the surface of a subject material until finally detected by two receiver transducers located at different distances from the sender [18-24].

The relation between travel-time measured by the L_{CR} wave and the corresponding uniaxial stress is derived by Egle and Bray [13] to be:

$$\Delta\sigma = \frac{E}{Lt_0}(t - t_0) \quad (1)$$

In Eq. (1), $\Delta\sigma$ is stress change, E is the elastic modulus and L is the acoustoelastic coefficient (known as acoustoelastic constant) for longitudinal waves propagated in the direction of the applied stress field. The acoustoelastic constant is measured by uniaxial tensile testing carried out on the samples extracted from the tested material. The travel time of the L_{CR} wave, t, is experimentally measured on the component, while t_0 is a reference time of the same on a stress-free sample.

2.2. Ultrasonic stress measurement using shear waves

Elastic waves are propagated in the isotropic solids with a velocity, which is characteristic for the material under test. The velocities of a longitudinal wave (V_L) and a shear wave (V_T) are given by Eq. (2) and Eq. (3), respectively.

$$\rho v_L^2 = \lambda + 2\mu = K + \frac{3}{4}\mu \quad (2)$$

$$\rho v_T^2 = \mu \quad (3)$$

In Eq. (2-3), ρ is the density, λ and μ are the Lame moduli and K is the bulk modulus. Furthermore, λ and μ describe the elastic behavior of the solid in the first approximation (Hooke's law). On an arbitrary plane jk, where i, j and k are the axes of a Cartesian system:

$$\left(\frac{v_{ij} - v_{ik}}{v_T}\right) = \frac{(2\mu + 0.5n)}{4\mu^2}(\sigma_j - \sigma_k) \quad (4)$$

In Eq. (4), the first index of V represents the direction of sound propagation while the second index is the direction of vibration, n is the third order elastic constant of the investigated material; V_{ij} and V_{ik} are the velocities of two shear waves polarized perpendicular to each other; σ_j and σ_k are principal stresses.

Knowledge of the material properties along with measured V_{ij} and V_{ik} in a plane stress state by employing ultrasonic birefringence theory leads to an estimate of the magnitude in the differences in principle stresses. By measuring the wave velocities, the absolute magnitude of stress can be achieved for a uniaxial stress state.

3- EXPERIMENTAL PROCEDURES

3.1. *Sample description*

The components characterized in this study were 6 mm plates made of ferritic stainless steel (AISI 430). Table1 shows the chemical composition of the material. Two plates, each 250 mm long in the weld direction and 120 mm wide, were joined using a submerged arc welding (SAW) process. A double butt-weld was performed without a gap between the plates using a 3.2 mm diameter 308 stainless steel filler metal. The weld reinforcement (excess weld metal) was removed with a 30000-rpm hand grinder prior to ultrasonic measurements. Thermal effects were mitigated by using a water-cooling system during grinding.

3.2. PWHT procedure

The welding procedure specifications was kept similar for welding eight samples, which underwent different heat treatments in order to investigate the effect of PWHT on residual stress. After the welding process, two samples (Sample 1 & 2) were immediately investigated by the ultrasonic method while the six other samples (Samples 3-8) underwent different PWHT procedures according to Table 2. In this study three different temperatures and two different holding times is considered for PWHT.

3.3. *Ultrasonic stress measurement devices (L_{CR} method)*

3.3.1. TOF measurement

According to the Eq. (1), time-of-flight (TOF) related to the ultrasonic longitudinal wave is needed to be accurately measured for an ultrasonic stress measurement. The TOF measurement devices, shown in Fig.1, include an ultrasonic box, computer, moving table, PMMA wedge and longitudinal ultrasonic transducers. The ultrasonic box is a 100 MHz ultrasonic testing device which has synchronization between the pulser signal and the internal clock, which controls an A/D converter. The internal clock has a resolution of 1 ns which allows very precise measurements of TOF. Three normal transducers (one sender and two receivers) assembled on an integrated wedge are employed to produce the L_{CR} wave. The wedge material was poly methyl methacrylate (PMMA) material, which was manufactured by using a laser cutting process. The TOF measurement was repeated in each point located in the scanning path, which is perpendicular to the weld line and passing from the weld centerline. The TOF was measured over a varying step size. For points near and on the melted zone (MZ), a step size of 2 mm was employed and this was progressively increased to 10 mm for points further away from the weld. Hence, about 30 points on each scanning path were measured. The moving table was used to position the wedge and transducers over the scanning path with a predetermined step size. The moving table was equipped with two vertical screws over the wedge for wedge positioning and also for keeping constant pressure on the wedge. This constant pressure, controlled by a load cell, was necessary to keep a constant couplant thickness between the wedge and stainless steel plate throughout the scanning path. Any change in the couplant film thickness can lead to a variation of TOF, which results in a measurement error.

It has been previously shown that the L_{CR} waves are able to penetrate in different depths of the material by changing the actuating frequency [16]. Hence, twelve transducers in four different testing frequencies (1 MHz, 2 MHz, 4 MHz and 5 MHz) were used. Three normal transducers with the same frequency were assembled in each wedge with elements having a diameter of 10 mm. The TOF was measured three times for each point and the average data was calculated. The path was scanned four times by employing four different frequencies of the transducers. As a result, 30 points on each scanning path were read 3 times using four testing frequencies and for eight stainless steel samples. Hence, a total of 2880 measurements were performed to obtain TOF using the L_{CR} method.

3.3.2. Determination of L_{CR} Penetration Depth

When a L_{CR} wave is propagated in a material with limited wall thickness, penetration depth of the L_{CR} wave is expected to be a function of frequency in which the ultrasonic transducers has been actuated. However, there is no definite relation between penetration depth of a L_{CR} wave and frequency. Hence, the penetration depth of the L_{CR} wave should be measured experimentally. A variable depth groove is cut in a plate, with the same material and thickness of the investigated samples, to create a barrier in order to physically prevent the L_{CR} wave from reaching the receiver transducer. It was found that a 1 mm deep groove completely blocked a 5 MHz L_{CR} wave, indicating that the penetration of this wave was 1 mm. Similarly, the penetration depth of 4 MHz, 2 MHz and 1 MHz L_{CR} wave was measured as 1.5 mm, 3 mm and 6 mm respectively.

3.3.3. Acoustoelastic constant measurement

To evaluate the acoustoelastic constant (L), tensile test samples were extracted from both sides of the plate. During the tensile test process, the TOF measurement devices were employed where the transducers were placed on the tensile test specimen in order to measure flight-time (t)

of the L_{CR} wave. This was repeated for stress-relieved, heat treated tensile specimens in order to obtain a comparison t_0 measurement. A standard uniaxial test machine was employed to increase the tensile stress in the specimen to different increments whereupon both t and instantaneous elastic modulus was measured. With this data, the acoustoelastic constant (L) was calculated with Eq. (1).

3.4. *Ultrasonic stress measurement devices (Shear wave method)*

3.4.1. TOF measurement

In the birefringence ultrasonic method, the velocity of two shear waves polarized in perpendicular directions is measured. For this measurement, the shear wave was generated by an ultrasonic transducer with a diameter equal to 13 mm, actuated at 2.25 MHz. The shear wave setup, shown in Fig. 2, was different from that used with the L_{CR} technique. Pressure on the transducer was maintained with a static reference weight and a moving table was not required. The excitation module and software employed for the L_{CR} technique was identical with that used for the shear wave technique. However, the shear wave technique required capturing both the wave direction as well as the TOF (Fig. 3).

3.4.2. Penetration Depth

As shown in Fig. 3, the operating principle of the shear wave transducer is that of a pulse-echo technique, permitting the measurement of average residual stresses in the component through-thickness. Penetration depth is not accessible via shear wave propagation techniques.

3.4.3. Acoustoelastic constant measurement

Measurement of the acoustoelastic constant was similar to that carried out for the L_{CR} method (mentioned in Sec. 3.3.3). TOF in stress-free samples was measured in an identical manner to that employed for the L_{CR} method. This process was followed even though the propagation behavior of the shear wave was different than the L_{CR} technique. In butt-welding, when the length of plates is more than the width, the longitudinal stress (parallel to weld line) is considerably greater than transverse stress (perpendicular to weld line). Hence, assumption of the unidirectional stress state is acceptable which simplifies Eq. (4) to:

$$\left(\frac{\Delta V}{V_0}\right) = \beta \times \sigma \qquad (5)$$

In Eq. (5), β is the acoustoelastic constant for the material. At each point, two shear wave velocities that propagate through the plate thickness are measured. The polarization, or particle vibration directions in these two types of waves are different. In one case particle vibration is parallel to weld line (V_{ji}) and in other case it is perpendicular (V_{jk}). The difference between the velocities of these waves is proportional to a stress value.

3.5. *Hole-drilling stress measurement*

Hole-drilling measurements were carried out in five different points on Sample 1 as shown in Fig. 4. The hole-drilling technique is a semi-destructive stress measurement method, capturing the strains relaxed by incremental drilling of a small hole with diameter of 1.5 mm. The depth of hole drilled for measurement was 2 mm, which resulted in an average stress across the 0-2 mm depth of material removal. After each drilling step, the strains were measured using a strain gauge rosette and the residual stresses were finally calculated employing equations established by ASTM: E837.

4- RESULTS AND DISCUSSION

4.1. Acoustoelastic constant measurement

To measure the acoustoelastic constant, each of eight samples underwent machining to produce two tensile test specimens from the base material and one specimen from the weld zone. Dimensions of these twenty-four tensile test specimens were of the Sheet Type (0.5 in. wide) conforming to ASTM: E8. By propagating the L_{CR} wave produced in four frequencies as well as the shear wave polarized in two directions, each specimen was tested six times to measure L and β. An example of these 144 measurements is shown in Fig. 5 for Sample 1. Here, the slope of the fitted trend line represents the acoustoelastic constant (e.g., L=2.48 or β =1.93 for the weld zone).

4.2. Ultrasonic stress measurement using L_{CR} waves

The longitudinal residual stresses (parallel to the weld line) were measured using L_{CR} waves. The stress measurement was carried out on the six different samples (Samples 3-8), which experienced different PWHT procedures (Table 2). However, two samples (Samples 1&2) were examined first in order to determine the as-welded level of residual stresses. Selecting two as-welded samples for investigation was pursued due to ascertain repeatability the subject ultrasonic stress measurement. The effect of PWHT on the residual stresses was then investigated by using four different testing frequencies to provide measurement of the sub-surface stresses.

4.2.1. Hole-drilling measurement to validate the L_{CR} stress-evaluation method

The capability of using the L_{CR} waves in the ultrasonic stress measurement has been confirmed in many previous studies [18-33]. However, the L_{CR} method is still considered an under-developed method, which necessitates verification by using other methods. Therefore, the results from hole-drilling and the 4 MHz L_{CR} method for Sample 1 were compared. This is a reasonable comparison as the hole-drilling technique provided an average stress over the entire 2 mm penetration, and the 4 MHz L_{CR} measurement penetrated to 1.5 mm, providing averaged results at this depth [16-17]. As shown in Fig. 6, there is an acceptable agreement between the hole-drilling results and those obtained from the L_{CR} method.

4.2.2. Determining the repeatability of the L_{CR} measurement method

The Samples 1 and 2 were welded by the same welding-procedure-specification (WPS) and did not experience PWHT. Hence, the same amounts of residual stresses are expected to remain in these samples. By comparing the results of the L_{CR} stress measurement for Samples 1&2, the repeatability of the measurement method is shown in Fig. 7. The L_{CR} measurement was carried out by using the 5 MHz transducer in order to compare the results of surface stresses. From Fig. 7, it is observed that residual stresses of the Sample 1 and Sample 2 have a little difference (less than 30 MPa) demonstrating the repeatability of the L_{CR} method.

4.2.3. Effect of PWHT temperature on residual stress

The effect of PWHT temperature is investigated by comparing the residual stress measured on Sample 3, 5 and 7 which have experienced PWHT in 700 °C, 760 °C and 820 °C, respectively (Fig. 8).

As shown in Fig. 8, the PWHT leads to a considerable decrease in the residual stress with a decreasing trend readily observable via the L_{CR} stress measurement method. The following observations can also be drawn from the trend shown in Fig. 8:

I. The peak residual stress in the as-welded plate (Sample 1) is equal to 360 MPa and decreases to 180 MPa, 200 MPa and 240 MPa for Sample 3, 5 and 7, respectively. This means that increasing the PWHT temperature had a negative effect leading to an increase in the peak RS post-treatment.

II. Increasing the PWHT temperature caused changes in the residual stress distribution. For instance, the residual stress distribution achieved for Sample 7 shows a new tensile stress zone (with the peak at 30 mm from the weld centerline) compared to compressive stress for Sample 1. The variations in the elastic stiffness and mass density around this zone could be cause of the result. The presence of this tensile region would be considered unacceptable by many manufacturers. This means that PWHT at 820 °C could be a damaging process for various applications that employ ferritic stainless steels, given the WPS and dimensions of the sample investigated.

III. The resolution of the L_{CR} method in a stress measurement of stainless steels has been shown to be ±30 MPa [16-17]. From Fig. 8, it is clear that the effect of PWHT temperature on the residual stress is higher than 30 MPa for the majority of measured points, particularly for the critical points located near the weld zone. Hence, the L_{CR} method can be considered accurate enough for the investigation of PWHT temperature on the residual stresses in ferritic stainless steels.

Therefore, PWHT at 700 °C is recommended for ferritic stainless steels (AISI 430) as the PWHT at 760 °C is more energy intensive with no improvement in stress minimization. However, PWHT at 820 °C is not recommended because of producing zones with high amounts of the tensile residual stresses.

4.2.4. Effect of PWHT time on the residual stress

The effect of PWHT time was investigated by changing the holding time at the annealing temperature from 1 to 3 hours for the stainless steel samples (Table 2). The results of measured residual stress for Sample 3 and 4 are compared in Fig. 9.

From Fig. 9, it is generally observed that extending the heat treatment time from 1 to 3 hours reduces residual stress. More specifically, the peak residual stress in Sample 1, 3 and 4 is equal to 360 MPa, 180 MPa and 130 MPa, respectively. This implies holding the welded plate at 700 °C for two more hours could lead to a reduction of about 27% in the peak of residual stress.

Similar conclusions can be made for the PHWT times investigated at 760 °C and 820 °C (Fig. 10). Unlike the PWHT at 700 °C, Fig. 10 shows that the trend of decreased peak residual stress with increased holding time is not observed, and at some locations, RS has increased with hold time. For example, the peak of residual stress is equal to 240 MPa and 269 MPa for Sample 7 and 8, respectively; this shows an increase of about 12% in the peak of residual stress by increasing the hold time from 1 to 3 hours. Therefore, in addition to the negative effect of increasing PWHT temperature, increasing the time for PWHT at 760 °C and 820 °C is not recommended.

4.2.5. Effect of PWHT on the sub-surface residual stresses

By changing the testing frequency in which the ultrasonic transducer is actuated, it is possible to penetrate in different depths and measure the sub-surface stresses. The results of sub-surface stress measurement are shown in Fig. 11 for Sample 1. The results show that increasing the depth of measurement decreases residual stress. The peak of residual stress is equal to 360 MPa, 324 MPa, 224 MPa and 130 MPa when the stresses are measured by 5 MHz, 4 MHz, 2 MHz and 1 MHz transducers, respectively. However, it is known from the previous studies that the measured stresses are the average of residual stresses [16-17]. For example, the 2 MHz transducer measures the average of residual stresses in the range of 0-3 mm from the plate top surface.

The decreasing trend of residual stress by increasing the depth of measurement is also observed in the heat-treated samples. For example, the sub-surface stress observations made for Sample 3 is shown in Fig. 12, which represents the same decreasing trend as seen in Sample 1.

The effect of PWHT time on sub-surface stresses was also investigated by comparing the results of different testing frequencies in Fig. 13. The results show that the effect of PWHT time on sub-surfaces stress is similar to the effect of PWHT on the surface stresses (Sec. 4.1.3 and 4.1.4). For example, the detrimental effect of PWHT at 820 °C on the residual stress distribution is observed to be a through-thickness effect which can be even seen at a 6 mm depth into the material. Furthermore, the capability of the L_{CR} method in distinguishing the PWHT effect on sub-surface stresses is one of the unique abilities of this method, which has been confirmed with this study.

4.3. Ultrasonic stress measurement using the shear waves

The residual stress for Samples 1-8 was measured using shear waves. Since the shear wave method employs the pulse-echo technique, the average of residual stresses through the thickness over a depth of 0-6 mm is measured; hence, it is not possible to validate the residual stresses obtained from the shear wave method with the hole-drilling measurement results. Instead, a comparison is possible between the results obtained via 1 MHz L_{CR} and shear techniques as this L_{CR} measurement provides comparable depth resolution (Fig. 14).

From Fig. 14, it is obvious that the shear wave is not as sensitive as the L_{CR} wave to stress, as reported by Egle and Bray [13]. There should be no residual stress at points located well away from the weld line, and this is not observed in the shear data, even at 40-90 mm away. This substantiates the L_{CR} method being more effective as opposed to shear. As the L_{CR} method employed in the present study has been validated via hole drilling, it is surmised that the difference between results obtained via shear and L_{CR} are error attributed to the shear technique. This difference is less than ±70 MPa and could be acceptable in stress analysis of stainless steels. The repeatability of the shear wave method is also investigated by comparing the residual stresses measured on Sample 1 and Sample 2, as shown in Fig. 15. The results seem to be a little cluttered and the repeatability divergence reaches to ±90 MPa in some points.

It is desirable to know whether the accuracy of shear wave method is enough for distinguishing the effect of PWHT on the residual stress, as it is a relatively uncomplicated measurement as compared to L_{CR}. Fig. 16 shows the comparison between the stress measured on Samples 1, 3, 5 and 7. The same comparison was accomplished by the L_{CR} method (Fig. 8), which showed that the residual stresses of as-welded sample are decreased by PWHT at 700 °C; a slight increase at 760 °C and a considerable increase along with an undesirable distribution of stress at 820 °C. A similar trend is very difficult to distinguish in Fig. 16. However, the residual stresses in Sample 1 are generally observed to be higher than the other samples and the Sample 3 could be interpreted to have the minimum of residual stresses. Hence, similar results to the L_{CR} method, which indicated favorable results by employing a 700°C PWHT are obtained by shear waves but lacking resolution.

Regarding the investigation of PWHT time, Fig. 17 shows the comparison between residual stresses measured for the samples that were held at 1 and 3 hours. From Fig. 17, it is not possible to reach the same conclusions by using the L_{CR} method (Sec. 4.1.4), as the difference between the hold times of 1 and 3 hours are not distinguishable. Hence, the resolution of the shear wave method is not enough to distinguish the effect of PWHT time on residual stresses.

4.4. Comparison between using the L_{CR} and shear waves in terms of measurement error

To compare the measurement error achieved by employing the L_{CR} and shear wave method in the field of ultrasonic stress measurement, it is desirable to define some relevant aspects as following:

A. Accuracy is defined as the amount of uncertainty in the stress measurement with respect to an absolute standard. In case of using the L_{CR} method for stress measurement, the absolute standard is the hole-drilling results (as shown in Fig. 6). However, as it is not possible to compare the hole-drilling results with those obtained from the ultrasonic shear method, the L_{CR} method serves as the absolute standard in this case (as shown in Fig. 14). Since there is no data to be served as the same absolute standard for both L_{CR} and shear wave methods, it is impractical to compare the accuracy of these two measurement methods.

B. Repeatability describes the reproducibility of the stress measurement in various measurement times. This has been addressed in Fig. 7 and Fig. 15 for the L_{CR} and shear wave method, respectively. From Fig. 7 and Fig. 15, the repeatability of the L_{CR} method is better than ±30 MPa while the repeatability is up to ±90 MPa for the shear wave method. This obviously shows higher repeatability achieved by the L_{CR} method in comparison with the shear wave method.

C. Resolution is expressed as the ratio between the maximum of stress measured in each point to the smallest part that can be resolved. In this case, the noise could be defined as differences between predicted stress in each point and the stress measured by the ultrasonic method. Based on this theory, the severe fluctuation observed in Fig. 16 and Fig. 17 can be interpreted as high amount of noise, i.e., low resolution. In comparison with the shear wave results, lower amount of noise (or higher resolution) has been achieved for the L_{CR} method as shown in Fig. 8-13.

D. Sensitivity is the smallest absolute amount of stress that can be detected by the ultrasonic method. The welding residual stresses are expected to be diminished in the locations far from the weld centerline. Hence, the points placed between 50 to 100 mm distances from the weld, as shown in Fig. 6, are supposed to show the smallest amount of residual stress that could be considered as a suitable verification of sensitivity test. Alternatively, if the measurement method is not able to present zero amount of residual stress in these point, it would be proved that the method is undesirably sensitive to another effects (e.g., microstructure, texture, environmental effects, etc.) in addition to the residual stress. From Fig. 14, it is obvious that stress-sensitivity of the L_{CR} waves are higher than the shear waves.

5- CONCLUSIONS

The main goal of this study was to compare the results obtained by using L_{CR} and shear waves for ultrasonic residual stress measurement. These results were then compared to gauge the efficacy of a PWHT in reducing residual stresses in welded ferritic stainless steel plates. A L_{CR}, shear wave and hole drilling stress-measurement techniques were employed. The results obtained from these measurements indicate:

1) There is an acceptable agreement between the hole-drilling measurement with those obtained from the L_{CR} method. However, due to the difference in effective depth of each technique, it is not possible to validate residual stresses obtained via ultrasonic

shear waves. A comparison was made between results obtained with 1 MHz L_{CR} and shear waves for validation purposes.

2) The results of both L_{CR} and shear wave method are the average of residual stress through the thickness of material. However, by changing testing frequency of the L_{CR} wave, it is possible to change the penetration depth in which the wave is propagated. As the shear wave method employs a pulse-echo technique, only residual stresses averaged through-thickness can be resolved.
3) Repeatability of the L_{CR} method is better than ±30 MPa while the repeatability is up to ±90 MPa for the shear wave method.
4) PWHT at 700 °C is recommended for ferritic stainless steels (AISI 430) while PWHT at 760 °C is more energy intensive with no improvement in residual stress reduction. More importantly, PWHT at 820 °C is not recommended because high amounts of the tensile residual stress can remain.
5) The L_{CR} method is considered an accurate enough method for correlating PWHT temperature with residual stresses in ferritic stainless steels. The shear wave method is also able to determine general effects of PWHT temperature on the residual stress, but with less resolution compared to the L_{CR} method.
6) According to the results achieved by the L_{CR} method, holding the welded plate at 700 °C for two more hours could lead to a reduction of about 27% in the peak of residual stress. Increasing the time for PWHT at 760 °C and 820 °C is not recommended because of the production of new stress distributions. However, the shear wave technique is not as sensitive as the L_{CR} and therefore cannot effectively resolve the effect of PWHT time on residual stress.

7) According to the results obtained by the L_{CR} method, the effect of PWHT time and temperature on sub-surfaces stresses is similar to the effect of PWHT on surface stresses.
8) The L_{CR} method is able to accurately distinguish the PWHT effect on the sub-surface stresses while this is not possible with the shear wave method.

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Table 1. Chemical composition of welded plates

C	Mn	P	S	Si	Cr	Mo
0.12	1	0.04	0.03	1	16	0.5

Table 2. Post weld heat treatment procedures

Sample	Holding temperature (°C)	Holding time (Hour)	Cooling procedure
Sample 3	*700*	*1*	*Air cooled*
Sample 4	*700*	*3*	*Air cooled*
Sample 5	*760*	*1*	*Air cooled*
Sample 6	*760*	*3*	*Air cooled*
Sample 7	*820*	*1*	*Furnace cooled to 600 °C then Air cooled*
Sample 8	*820*	*3*	*Furnace cooled to 600 °C then Air cooled*

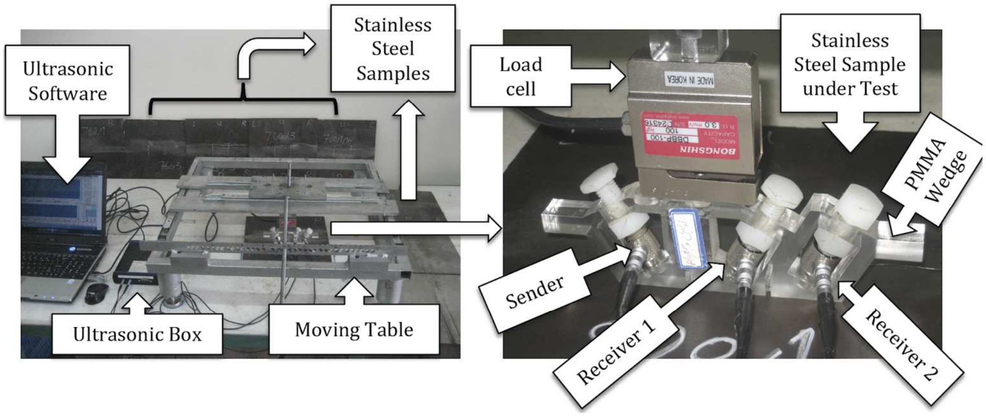

Fig. 1. Experimental setup for TOF measurement by using the LCR wave
151x62mm (300 x 300 DPI)

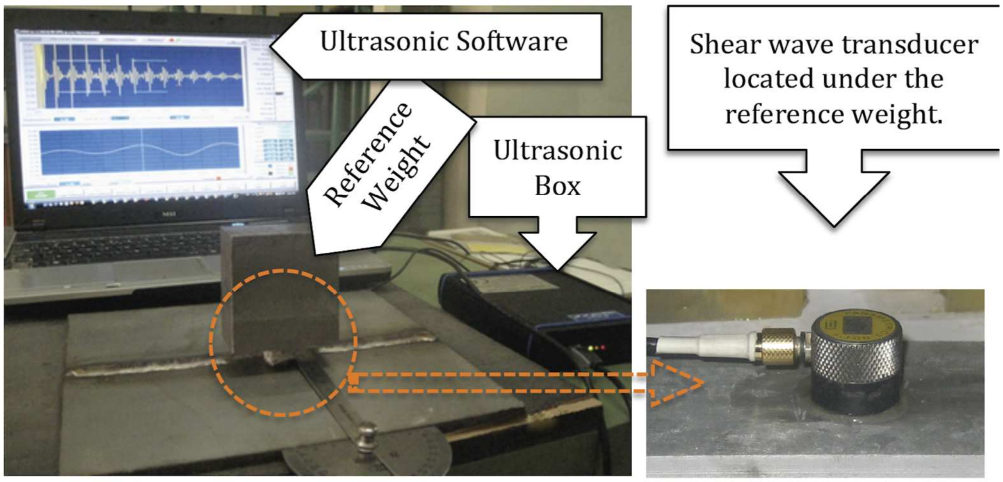

Fig. 2. Experimental setup for TOF measurement by using the shear wave
151x73mm (300 x 300 DPI)

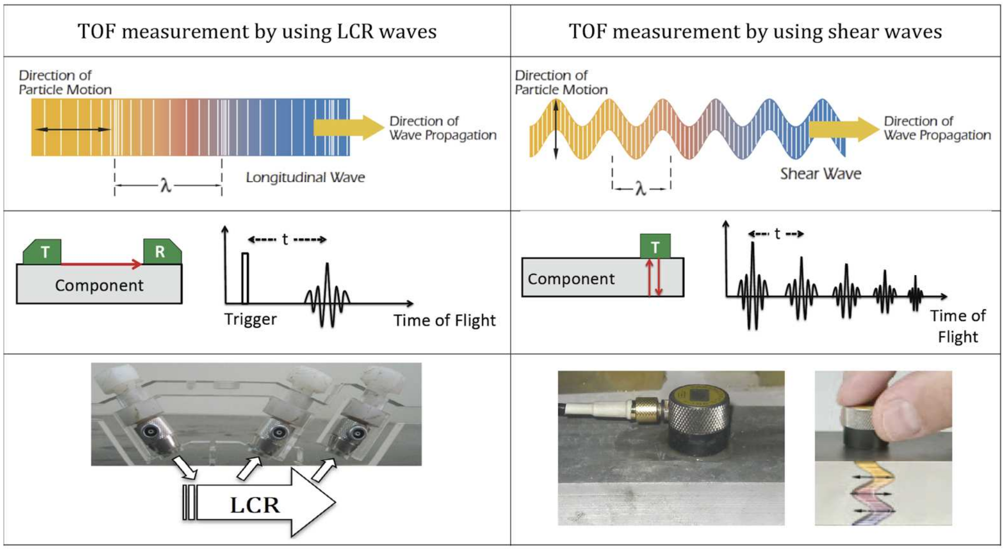

Fig. 3. Comparison between using the LCR and shear wave for TOF measurement
160x89mm (300 x 300 DPI)

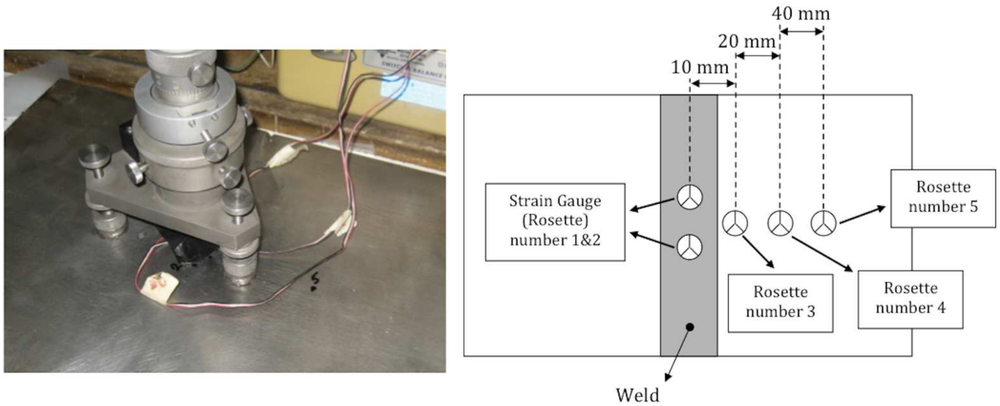

Fig. 4. Hole-drilling stress measurement on Sample 1
160x67mm (300 x 300 DPI)

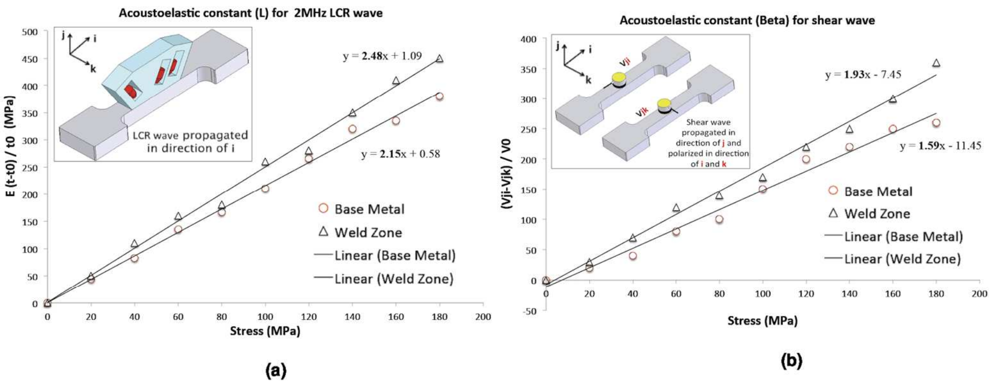

Fig. 5. Acoustoelastic constant measured by (a) 2MHz LCR wave and (b) shear wave
159x60mm (300 x 300 DPI)

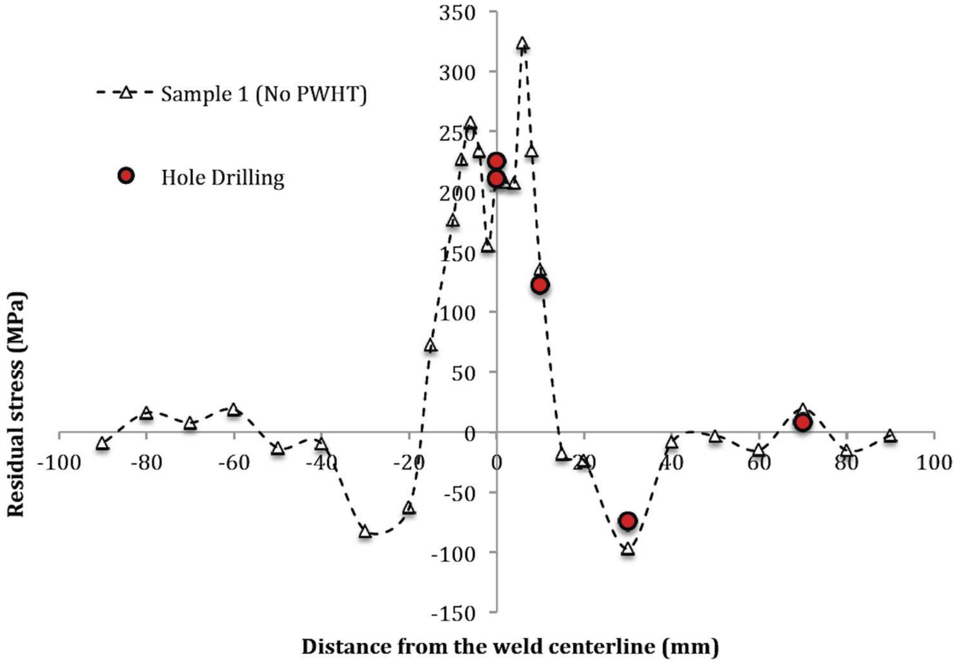

Fig. 6. Validation of the LCR stress-evaluation results by employing the hole-drilling method
159x114mm (300 x 300 DPI)

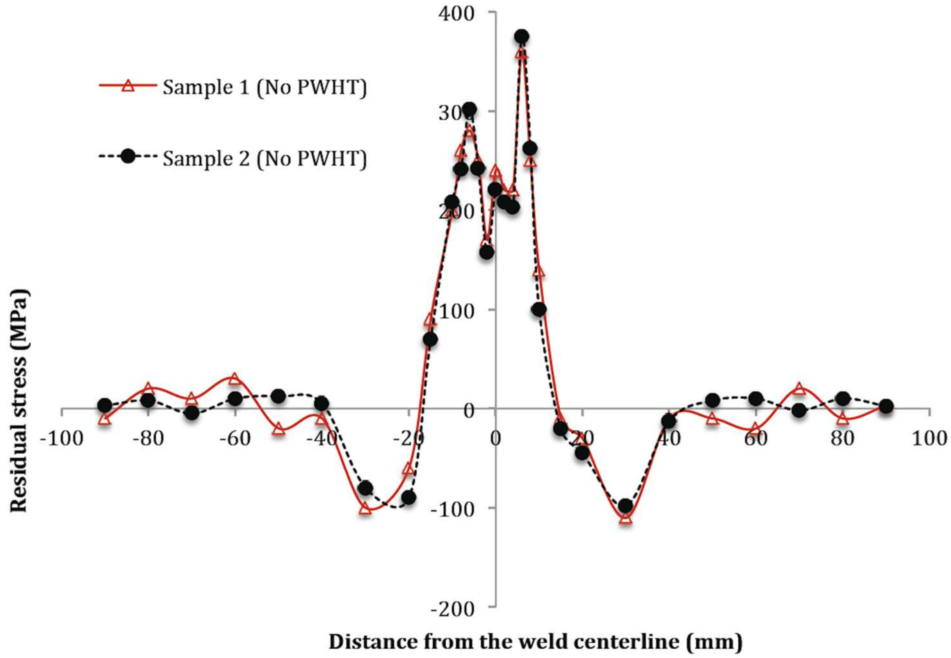

Fig. 7. Repeatability investigation of the LCR method
160x108mm (300 x 300 DPI)

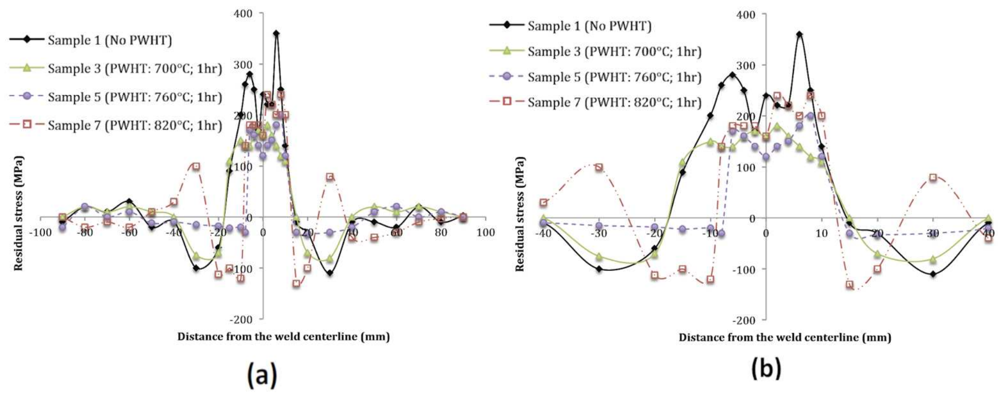

Fig. 8. The effect of PWHT temperature on the residual stress (a: Thorough the plate; b: -40 to 40 mm distance from the weld centerline)
160x63mm (300 x 300 DPI)

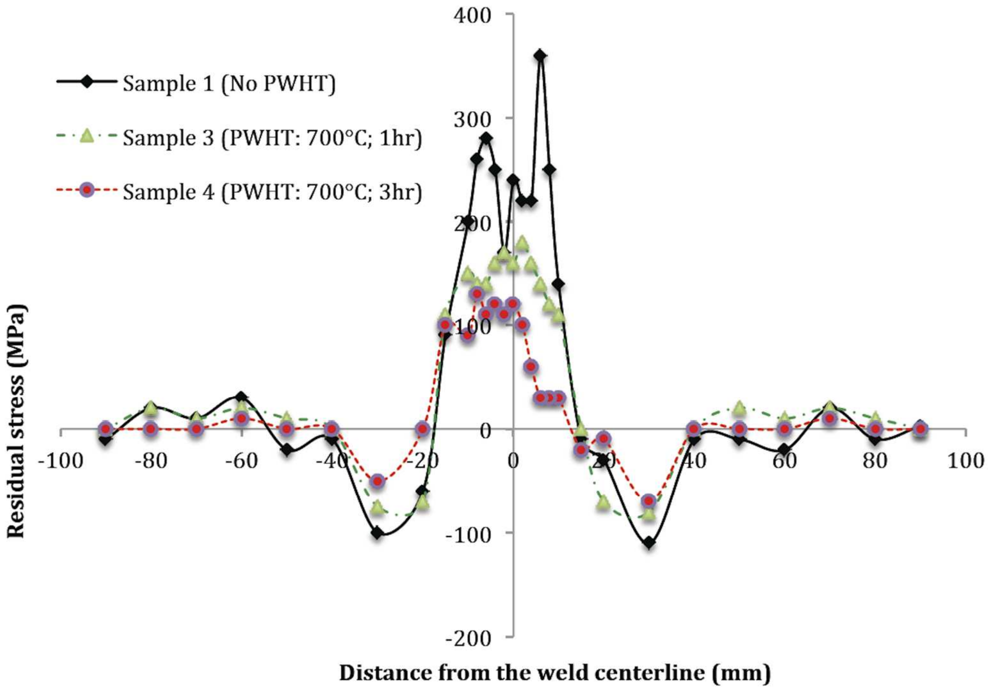

Fig. 9. Effect of PWHT time on the residual stress (PWHT at 700 °C)
160x109mm (300 x 300 DPI)

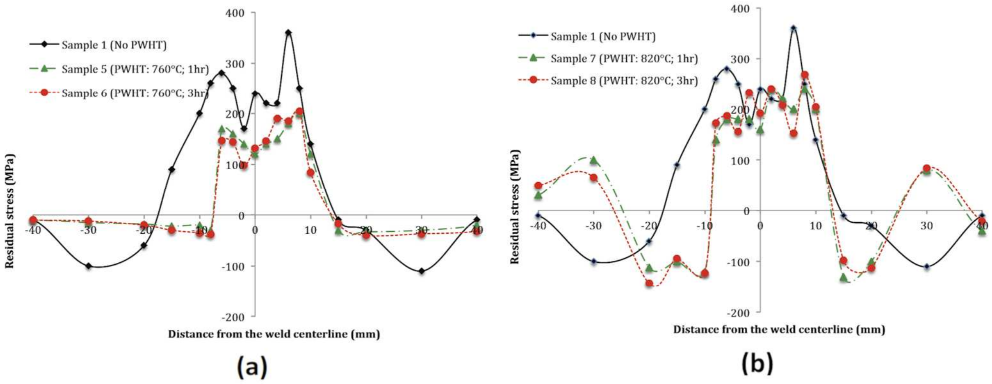

Fig. 10. Effect of PWHT time on the residual stress (a: PWHT at 760 °C; b: PWHT at 820 °C)
154x60mm (300 x 300 DPI)

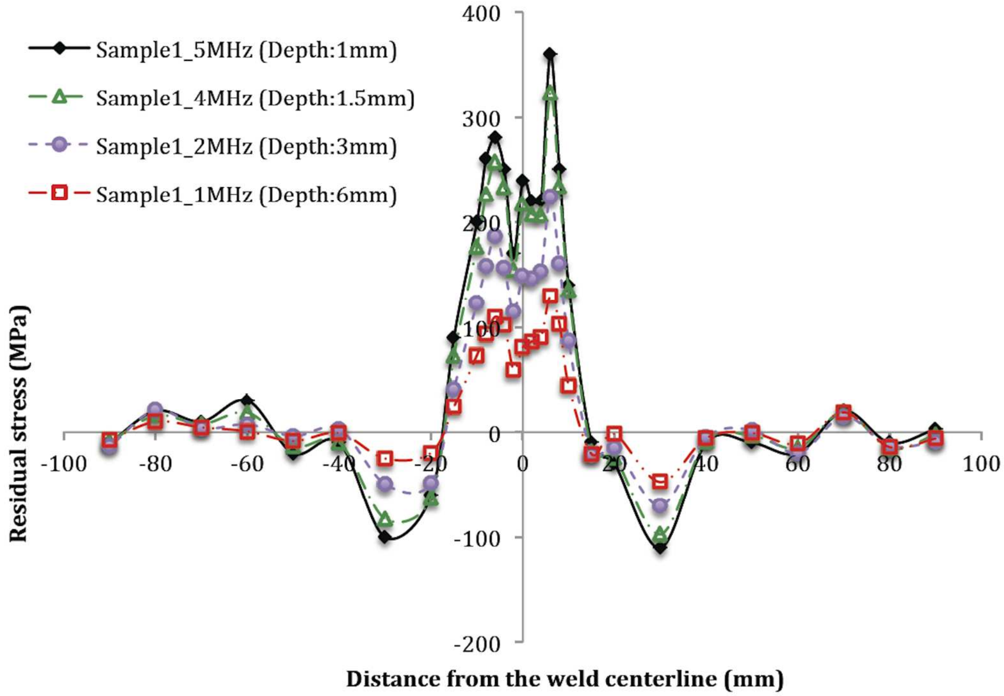

Fig. 11. Sub-surface stress measurement in Sample 1
157x109mm (300 x 300 DPI)

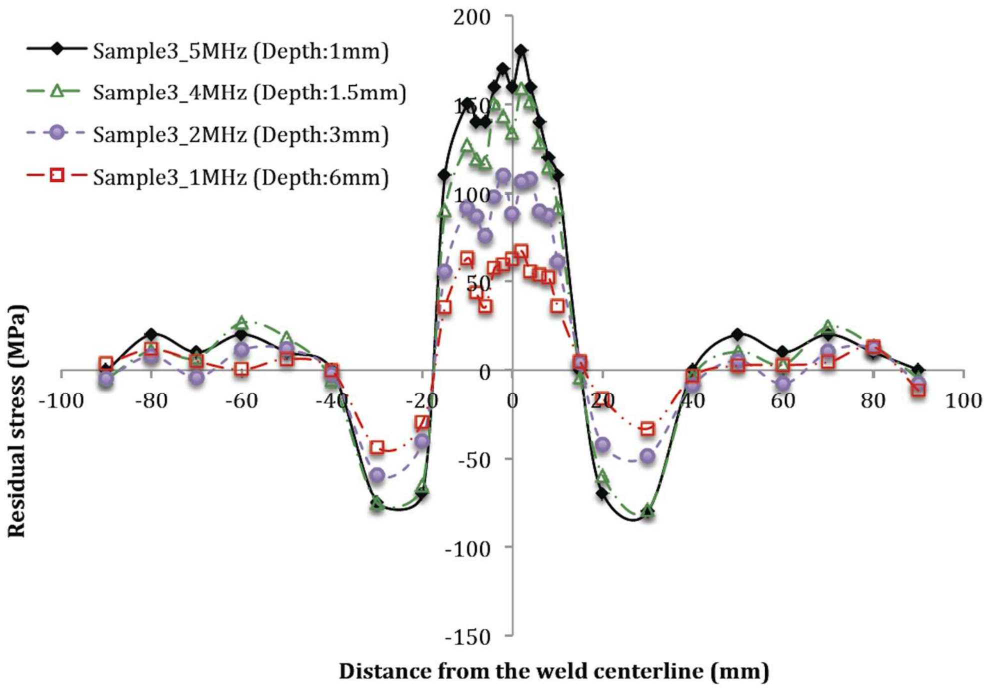

Fig. 12. Sub-surface stress measurement in Sample 3 (PWHT at 700 °C for 1 hour)
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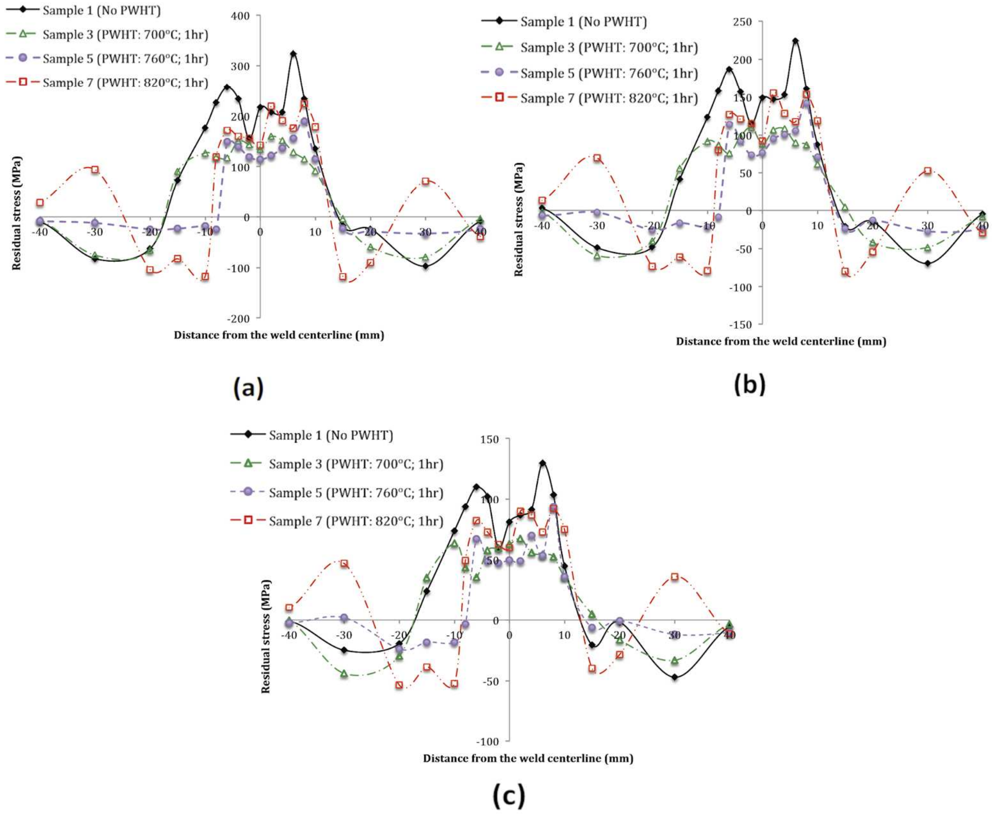

Fig. 13. The effect of PWHT on the sub-surface residual stresses measured by employing (a) 4 MHz, (b) 2 MHz and (c) 1 MHz transducers
160x133mm (300 x 300 DPI)

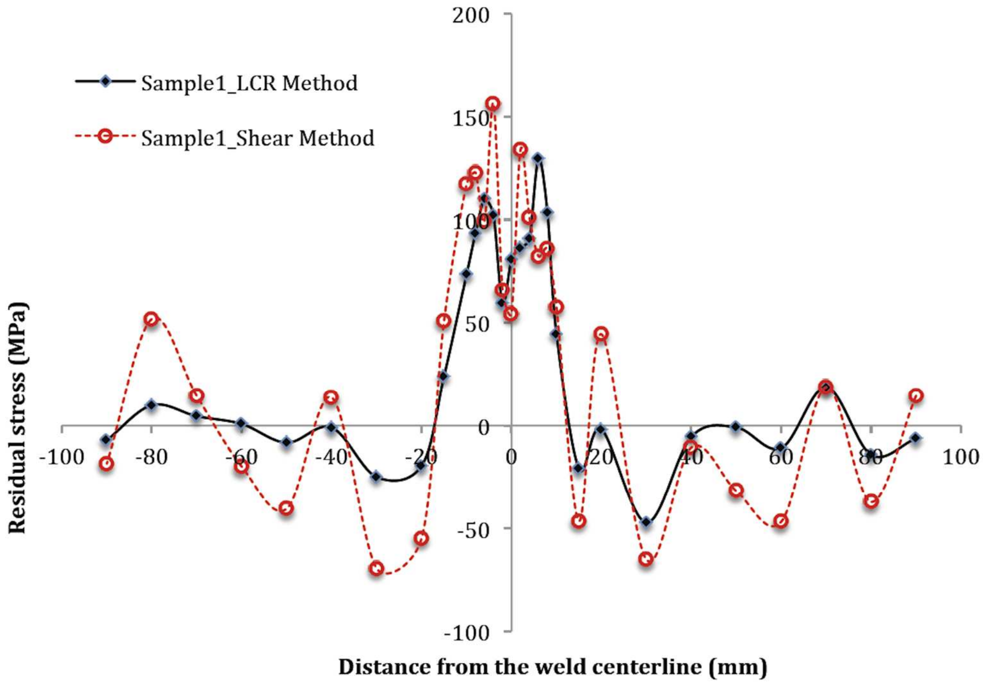

Fig. 14. Comparison between shear and LCR wave in the ultrasonic stress measurement
155x109mm (300 x 300 DPI)

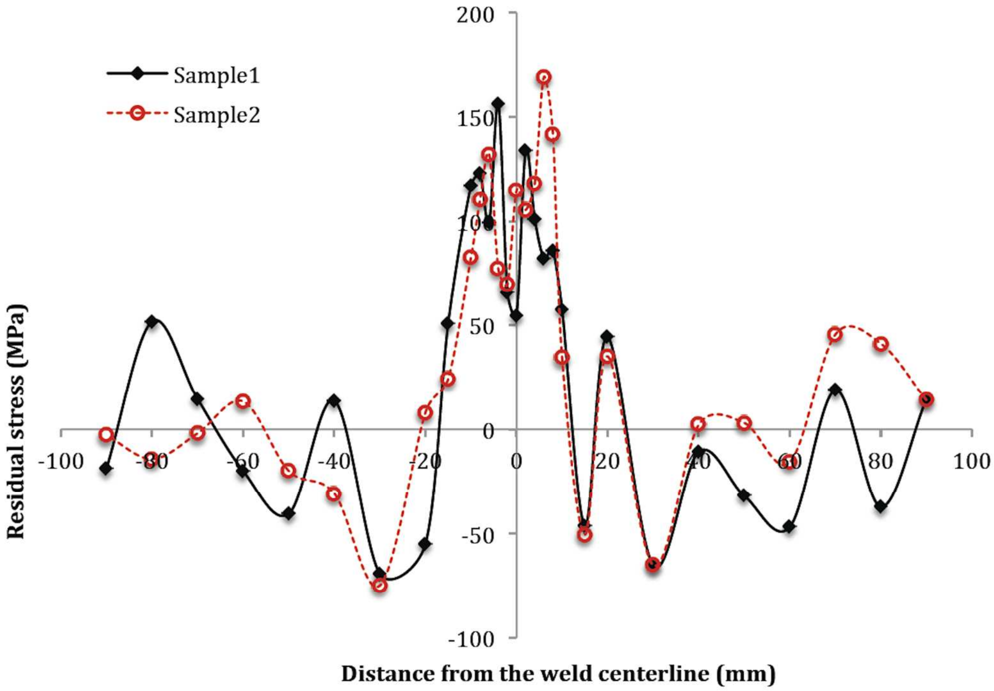

Fig. 15. Repeatability of the shear waves used for the ultrasonic stress measurement
157x109mm (300 x 300 DPI)

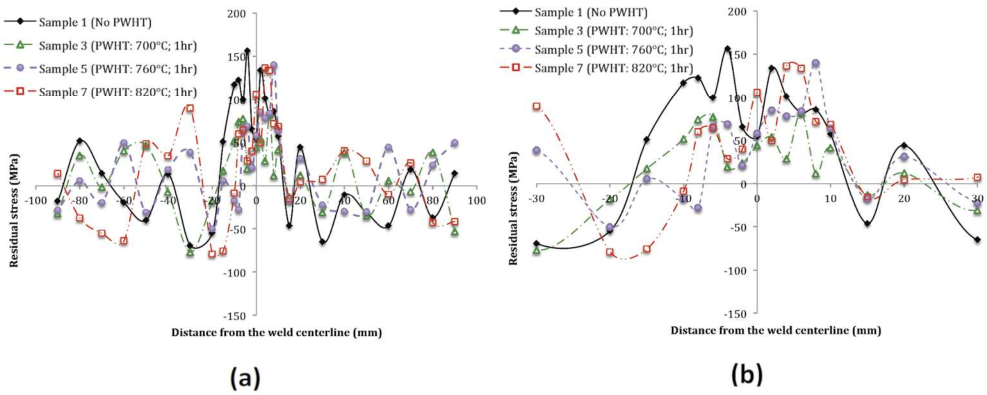

Fig. 16. Investigation of PWHT temperature by using shear-wave stress-measurement method (a: Thorough the plate; b: -30 to 30 mm distance from the weld centerline)
160x63mm (300 x 300 DPI)

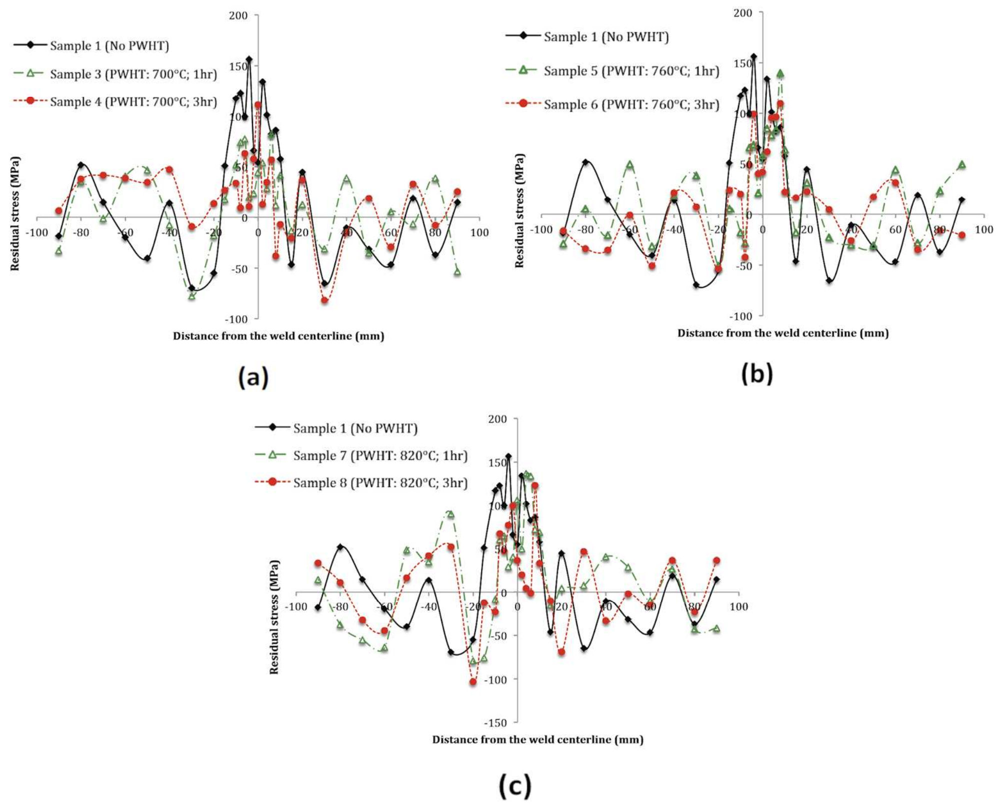

Fig. 17. Investigation of PWHT time by using shear-wave stress-measurement method
160x129mm (300 x 300 DPI)