Residual Stress Evaluation In Austenitic Stainless Steel Butt Weld Joints By Ultrasonic Technique

P. Palanichamy*, A. Joseph*, K. V. Kasiviswanathan*, D. K. Bhattacharya* and Baldev Raj*

This paper discusses the results of measurement of residual stress pattern across butt weld joints by ultrasonic velocity measurements in 15 mm and 47 mm thick AISI type 304 stainless steel plates. These are supplemented by results obtained from hole drilling strain gauge measurements. Pulse echo overlap technique was used to measure the through thickness longitudinal ultrasonic velocities. Acoustoelastic constant was determined to convert the change in ultrasonic velocities to residual stress values. The residual stress pattren obtained by the two techniques showed similar trends. Brief overview of various other residual stress measurement methods, and various techniques for ultrasonic velocity measurements are included in the paper.

KEY WORDS **Residual stress, Austenitic stainless steel, Weld Joint, Ultrasonic Velocity, Acoustoelastic constant, strain guage technique**

A. INTRODUCTION

Residual stresses are the locked in stresses generated due to nonuniform deformation at different parts of a component. They are sometimes referred to as internal stresses or locked-in stresses. The maximum value to which the residual stress can reach is the elastic limit of the material. A stress in excess of this value with no external force to oppose it will relieve itself by plastic deformation until it reaches the value of yield stress.

In a polycrystalline material, residual stress can be classified into three types. Residual stress of the first type (macroscopic residual stress) is nearly homogeneous over the region of many grains. It is defined as the stress averaged over an area of many grains. The residual stress of the second type (microscopic residual stress) is nearly homogeneous over a small region of a material, usually the size of one or part of a grain. The residual stress of the third type (submicroscopic stress) is non-homogeneous even in a very small region of the order of several lattice dimensions. Submicroscopic residual stress is caused primarily by lattice defects in crystals, such as point defects, line defects etc. Microscopic residual stress occurs in single and multiphase materials, because of the difference in thermal or elastic / plastic properties of the multiphases. Residual stresses can be induced in the grains by heat or chemical treatment or by mechanical loading. The stress developed by pile up of dislocations is an example that occurs due to mechanical loading. Another example is the precipitation of second phase particles in solid solution. Macroscopic residual stress is generally caused by inhomogenous plastic strains in a structure.

In general, residual stresses induced in a structure are the sum of all three stress types metioned above. We can occasionally identify each of them separetely. For engineering applications, it is the macrostresses that are important.

In a weld joint, significant residual stresses are present due to nonuniform cooling rates at different points in the weld metal and heat affected zone. The situation is of practical concern in the case of austenitic stainless steels since they have poor thermal conductivity and high thermal expansion conficients which are responsible for higher levels of residual stresses.

Since the presence of residual stresses affect many important properties, it is necessary that the spatial pattern of such stresses are known before a component is put in service. Several methods have been found to be useful for the measurement of these stresses. They can be categorised as destructive, semidestructive or nondestructive depending on the extent a component is damaged at the location of measurement. It is the nondestructive technique that is important for industrial use. The technique based on ultrasonic velocity measurement is one of the NDT techniques that have attracted attention from many investigators since such techniques would be simple to use, if appropriately developed and calibrated.

This paper discusses the results of ultrasonic technique (based on the measurement of longitudinal bulk velocity) used for the measurement of residual stresses

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at the butt weld joints in AISI type 304 stainless steel (SS) plates of 15 mm and 47 mm thickness. The results are compared with those measured by strain gauge technique.

To give a better prespective of the ultrasonic techniques in relation to other techniques, and among the ultrasonic techniques the relevance of the specific technique used in the work, a short overview is first given on various techniques available for the measurement of residual stresses, which is followed by another short overview on various ultrasonic velocity measurement techniques. These are followed by experimental results and discussion on the present work.

B. Techniques For Measurement Of Residual Stresses

The following experimental techniques are available for the measurement of residual stresses : (a) photoelasticity and other optical techniques (b) strain gauge technique (c) X-ray diffraction (d) neutron diffraction (e) Barkhausen noise and (f) ultrasonics.

The photoelasticity technique is dependent on the change in the refraction and polarisation characteristics of light in transparent photoelastic materials as a function of stress[1]. For opaque metallic components, an equivalent transparent model and simulated loading system is required.

Strain gauge technique relies on the contraction and expansion in thin metallic foils (strain gauge) bonded on a component surface, when locked in residual stresses are released by dissection, saw cutting, ring coring, or hole drilling [2 to 6]. The contraction and expansion change the resistance of the strain gauges, which can be correlated with the strains and thereby stresses. Elasticity theory provides the basis for estimating the magnitude and direction of the stresses. Truly speaking, this technique is never nondestructive.In some cases, it can at the most be called semi-destructive. It is however an important technique for calibration of other techniques and useful during prototype development.

X-ray diffraction technique depends on the phenomenon that elastic strain changes the seperations between parallel crystallographic planes[7]. X-ray technique is capable of measuring macro and micro residual stresses. Macro residual stresses are estimated from the displacement of diffraction peaks. Micro residual stresses are estimated from the new peak position appearing as spots shifted from the new diffraction line position. Portable X-ray diffraction equipment are now readily available. The main limitation of this technique is the inability of the X-ray beam to penetrate far into the material. It is essentially a surface technique. It is also affected by texture and is time consuming. The penetration of neutrons is a few orders more than X-rays thus proving information for bulk material. This technique, however, is not a practical proposition since nuclear reactors with good collimated neutron beam tubes are required as neutron source [8 to 11].

Barkhausen noise analysis technique uses the magnetic perturbation signal and/or the acoustic signal generated in a ferromagnetic material when an induced magnetic field is swept through it in a hysteresis loop. Such signals are strongly affected both by microstructure and stress. Therefore characterisation of the signal is needed to remove the effect of microstructure. Each material and component system requires individual calibration. Although this technique has been used in simple cases, it cannot be said that it is well established. Information on the measurement of residual stresses using magnetic Barkhausen noise and acoustic Barkhausen noise can be Referred [12 to 15].

Ultrasonics has found a prominent place in NDT for defect and materials characterisation. One of the important parameters in ultrasonics is velocity which has been used to assess microstructure, density, texture, modulus, and residual stress [16 to 23]. So far as residual stress measurement is concerned, the ultrasonic technique through the measurement of ultrasonic velocity is not yet well proven since the results are affected by texture, microstructure, difficulty in reproducible probe/specimen contact. More investigations on this technique and the comparision of the results obtained by this technique with those obtained by other proven techniques such as strain gauge measurement and X-ray diffraction are needed for reliable use in field applications.

The ultrasonic velocity can be measured as volume velocity during its passage through the volume of a material to find out the stresses averaged through the volume or as the surface velocity to find out surface residual stresses [24]. In this work, the volume velocity has been used to find out the variation of through thickness averaged residual stresses in welded plates. There are commonly three methods available for the measurement of volume velocities [25]. (a) Sing-around method, (b) Pulse superposition method, and (c) Pulse overlap method. In the present work, a pulse overlap method [26] has been used, and a brief account is given on the three methods of ultrasonic velocity measurements.

C. Techniques For Ultrasonic Velocity Measurements

C.1 Sing-Around Method

In this method, a triggered transmitter send an electrical pulse to the transmitting transducer which generates a mechanical wave in the specimen. This wave is received by the receiving transducer or by the same transmitting transducer and amplified. The leading edge of the received and amplified signal is used to generate a trigger signal that initiates a new pulse from the transmitter. This loop runs continuously. The frequency of occurrence of the trigger signal is measured by a frequency counter. The travel time through the loop is the reciprocal of the number of trigger signals counted per second. From this, velocity is calcualted for the known path length.

C.2 Pulse Superposition Method

In this method, a singal transducer is used on the specimen, and multiple echoes are observed. The method is called "Pulse superposition" because the ultrasonic pulses are actually superimposed within the specimen. Echo 1 from a pulse is superimposed upon echo 2 from preceding pulse, echo 3 from the one before that, echo 4 from the still earlier one, and so on. The superposition is made possible by the use of a continuous wave (cw), imposed on the RF pulse. When the frequency of the continuous wave is adjusted to the travel time of the ultrasonic wave, an absolute maximum occurs in the superposed signal because of constructive interference. Inverse of the cw frequency gives the ultrasonic transit time.

C.3 Pulse–Echo Overlap Method

The pulse-echo overlap method is a versatile and relatively simple method that gives accurate measurement of ultrasonic waves in materials. The accuracy arises fron the fact that the method is capable of measuring the transit time accurately from any cycle of one echo to the corresponding cycle of the next echo. The method is able to handle diffraction (beam spreading) and phase correction properly [25]. The principle of measurement in this method is to make two successive back echo signals of interest to overlap on the oscilloscope by driving the X-axis with a carrier frequency whose period is the travel time between the signals of interest. Then one signal appears on one sweep of the oscilloscope, and the other signal appears on the next sweep. Figure 1 shows the block diagram of the pulse-echo system. Figure 2 shows tracings obtained from oscilloscope screen explaining the principle of the method.The frequency resolution in the system used is one in ten power six [26].

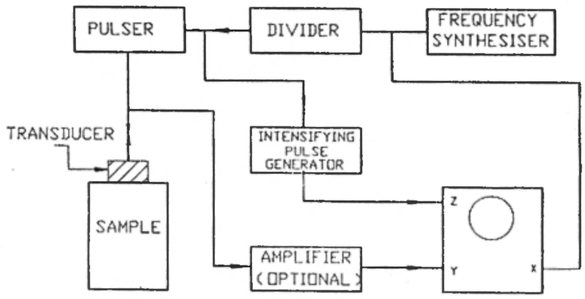


Fig.1. Block Diagram Of The Pulse - Echo - Overlap System

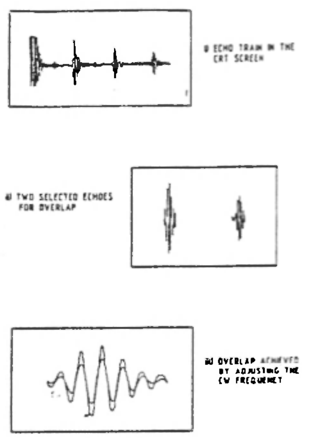
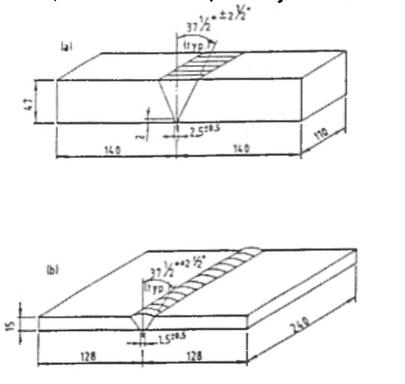


Fig. 2. Sequence of Overlap of any Two Echoes



ALL DIMENSIONS ARE IN mm

Fig. 3. Stainless Steel Weld Pads

D. Experimental

D.1 Specimen Preparation

Butt weld joints were prepared in AISI type 304 SS plates of 15 mm and 47 mm thickness by manual metal arc welding process. The weld configurations are shown in Fig. 3. In the case of 47 mm thick weld, the weld crown was machined off to facilitate ultrasonic velocity measurement in the weld region. The machined weld pad was used for all the experiments.

D.2 Determination of Acoustoelastic Constant

Acoustoelastic constant is defined by the following equation [27]:

V_L = V_{LO} + A , where = stress

VL = Ultrasonic velocity in material under Stress

V_{LO} = Ultrasonic velocity in the stress free material

A = Acoustoelastic constant.

A flat tensile specimen of annealed AISI type 304 SS was prepared and tested using a universal tensile testing machine of maximum capacity 100 tonnes.The gauge length portion where uniform elongation occurs was earlier calibrated on a similar specimen with etched grid markings and observing the gird deformations.With no load, ultrasonic velocity was measured through the thickness of gauge length using pulse-echo overlap technique as discussed earlier. A 2 MHz commercial longitudinal beam ultrasonic probe was used. Measurement of ultrasonic velocity was repeated with increasing tensile load. Figure 4 shows the percentage increase in the velocity as a function of increasing stress in the specimen. The slope of the straight line found by regression analysis gives the desired acoustoelastic constant.

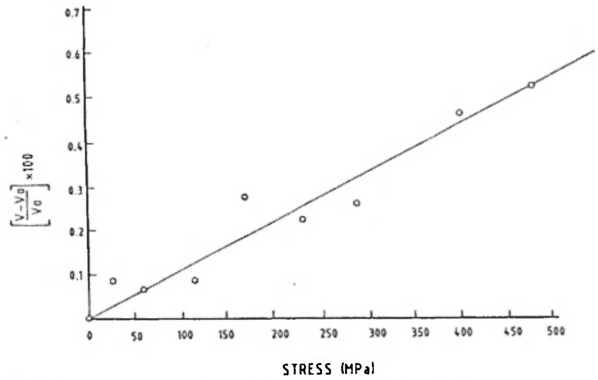


Fig. 4. Percentage change in ultrasonic velocity as a function of applied stress in AISI type 304 SS the slope gives the acousto elastic constant.

D.3 Measurement of Residual Stress by Ultrasonics

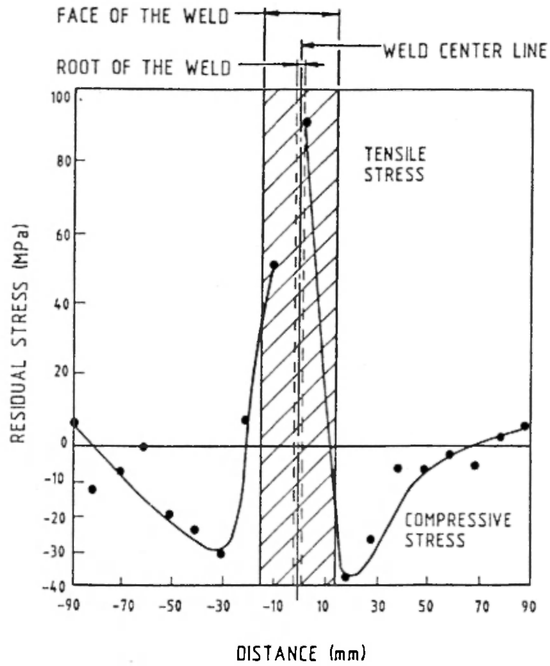


Fig. 5. Residual Stress vairation across the weld in 15mm. thick AISI type 304 SS pad obtained by ultrasonic Technique.

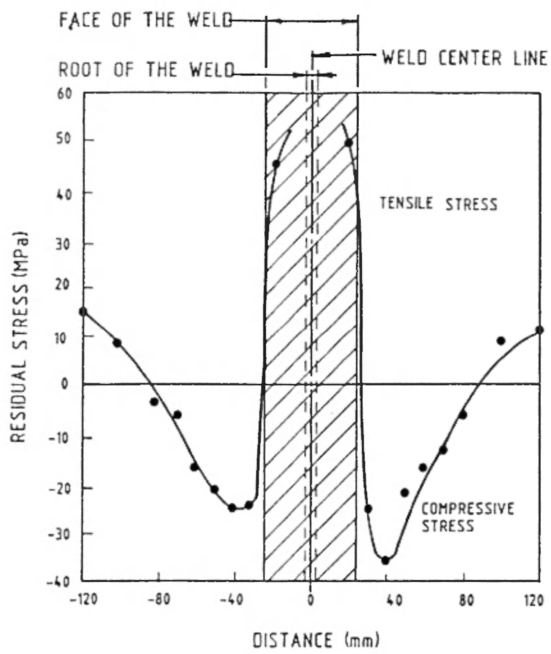
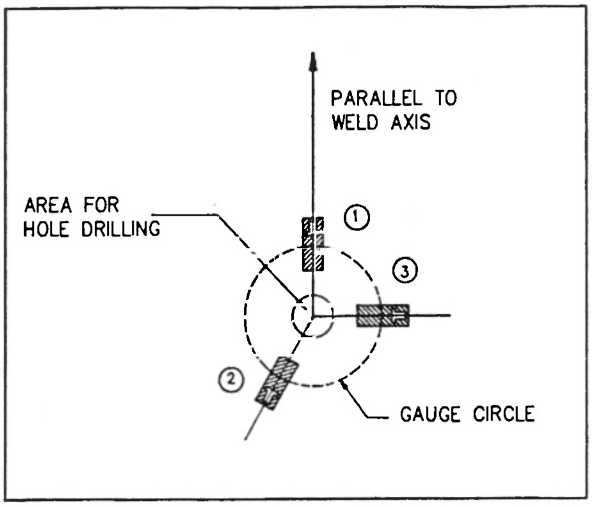


Fig. 6. Residual Stress Vairation across the weld in 47 mm. thick AISI type 304 SS pad obtained by ultrasonic Technique.

Ultrasonic velocities were measured along a line perpendicular to the weld axis by using the same 2 MHz longitudinal wave probe that was used for the measurement of acoustoelastic constant. Relative changes in the velocities were converted into stress by using the acoustoelastic constant measured earlier. (Fig 5 and 6) show the variation in the residual stress along a line perpendicular to weld axis and on either of its side in the 15 mm thick and 47 mm thick plates, respectively.

D.4 Measurement of Residual Stresses by Strain Gauge Method

Subsequent to the measurement of the residual stress pattern by ultrasonics, strain gauge method was used to obtain the residual stress pattern. The configuration of the strain gauge rosette used is shown in Fig 7



1, 2, 3 – STRAIN GAUGE ELEMENTS

Fig. 7. Strain Gauge Rosette Arrangement

This arrangement is as per ASTM standard E- 837 - 85 [28]. Such rosettes were pasted at various locations so that the centre of a rosette lies on the same line along which the residual stress pattern was measured by ultrasonics. The orientation of the rosettes were such that one of the two perpendicular elements were aligned along the weld axis and the other perpendicular to it. This was done to facilitate measurement of stresses in axes paraLLeL and perpendicular to the welding direction. Holes using a 1.59 mm diameter milling cutter suitable for austenitic stainless steel materials, were drilled at the centre of the resettes, to a depth of about 2 mm and the strains experienced by individual members of the rosettes were monitored. From the strain values, the stresses in the principal directions were calculated by strandard method [28].

Fig. 8 shows the stress distributions as obtained by the above procedure on the 15 mm thick weld pad, in a direction parallel to the weld axis. Figure 9 gives the stress distribution for the 47 mm thick weld pad

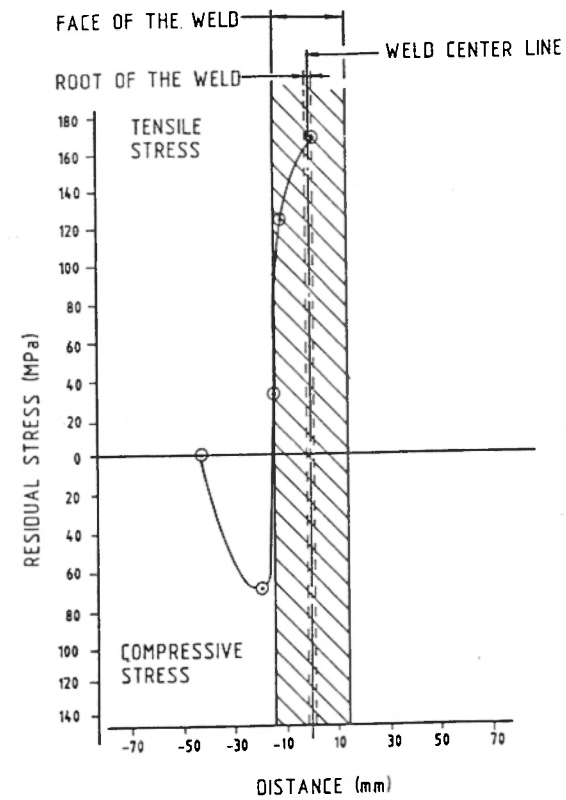


Fig. 8. Residual stress variation across the weld in 15 mm thick AISI type 304 SS pad obtained by hole drilling strain gauge techniques (stress parallel to weld direction)

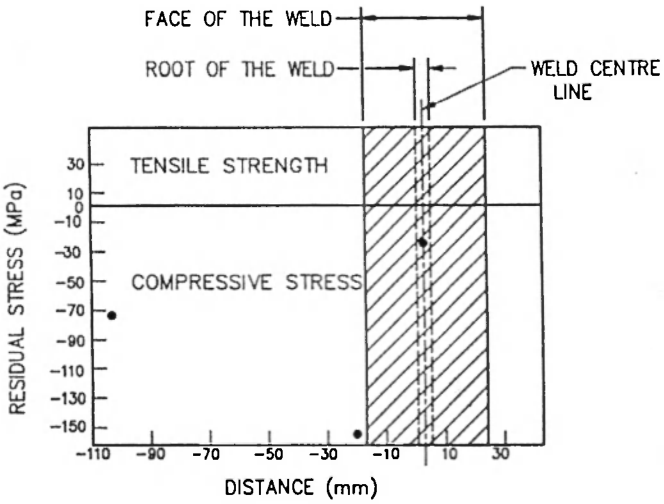


Fig. 9. Residual stress variation across the weld in 47 mm thick AISI type 304 SS pad obtained by strain gauge technique (parallel to welding direction)

E. Discussion

Residual stresses are produced in a weldment and adjoining heat affected zone (HAZ) due to the non-uniform plastic deformation which takes place on heating and cooling during the process of welding. Residual stresses can be attributed to the temperature distribution in and around the weld and the resultant thermal stresses. Distribution of temperature depends upon many factors such as thickness of plate, size of plate, speed of welding, position of weld and thermal properties of the plate. Several experimental and theoretical methods of measurement and analysis of residual stresses in the weldments have been reported [29 32]. In general, the residual stress pattern associated with welding shows tensile stresses of high magnitude in the weld region. This tapers off rapidly to bocome compressive in nature in the HAZ. Beyond HAZ, the pattern moves towards the stress value in the parent metal unaffected by welding.

(Fig. 5,) depicts the residual stress pattern observed in the case of 15 mm thick weldment by ultrasonic method. The stresses at the weldment are tensile in nature and change over to compressive at the HAZ. The pattern again become tensile further away at the parent metal. A similar trend can be also seen in the case of 47 mm thick plate weldment from (Fig. 6,) except at the weld centre line, where ultrasonic technique could not be used due to intense scattering owing to the thick textured weldment. As can be seen from this figure, the measurements shown on the weld are away from the weld centre line on either side and velocities measured at these points correspond to only part of the weld material, the rest being the parent material. This is due to the geometry of the weld groove. The trend seen in (Fig. 5 & 6) is in conformity with the report in austenitic weldments [29].

When (Fig. 5) is compared with (Fig. 8), similarity in the stress distribution pattern is observed. However the absolute values of the measured stress at corresponding points from the two figures can not compared since the strain gauge method gives only the subsurface stress distributions (for a depth approx. 2 mm), whereas the ultrasonic method used in this work pertains to the stress distribution averaged through the thickness of the plate.

The similarity in the stress pattern can also be seen in the (Fig. 6 & 9) for ultrasonic measurement and hole drilling method respectively in the case of 47 mm thick plate, except the measurement in the weld region. In this region the strain gauge measurement has indicated a compressive stress. As described earlier ultrasonic stress measurement could not be carried out on the weld area. A possible reason for the compressive stress at the weld centre line, as observed by strain gauge technique could be due to the machining of the weld crown as explained earlier, prior to the stress measurements.

F. CONCLUSIONS

An ultrasonic method using pulse-echo overleap technique has been succesfully developed to map the residual stress patterns at butt weld joints. The results on residual stress measurement by ultrasonic technique have been supplemented by strain gauge technique in the case of 15 mm & 47 mm thick AISI type 304 SS weld joints. In general, similarity in the stress distribution pattern measured by the two techniques was observed. It is concluded that ultrasonic technique can be in an effective manner for residual stress measurements at weld joints. However, precision instrumentation for velocity measurement and extensive prior calibration are prerequisites to the use of ultrasonic technique.

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