NONDESTRUCTIVE MEASUREMENT OF RESIDUAL STRESS IN CARBON STEEL WELD JOINTS

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INTRODUCTION

The knowledge of the nature and magnitudes of residual stress (RS.) in a weld joint is important for avoiding distortions and premature failures. Both analytical and experimental techniques are used for getting information on RS distributions [1,2]. Since theoritical calculations are not easy, and also because the calculated values require verifications, experimental determinations of RS profiles are essential. Strain gauge hole drilling technique can be used to measure sub-surface RS, strain gauge dissection technique can be used to measure the through thickness RS variation. These techniques are destructive, time consuming and require a careful analysis of the data for reliable results. Therefore, nondestructive techniques are preferred for residual stress measurements. The nondestructive techniques employed to obtain the residual stress profiles across the weld joints were :

(1) X-ray diffraction technique

(2) Ultrasonic technique, and

(3) Magnetomechanical acoustic emission technique of MAE (also known as Acoustic Barkhausen noise analysis). In this study, RS measurements in 8 mm and 12 mm thick mild steel weld joints in as welded condition and after annealing at 873 K for two hours were carried out.

Specimen Preparation

Hot rolled IS 226 mild steel plates were used for the preparation of weld pads. The butt weld joints were prepared by manual metal arc (MMA) welding process in single groove weld design using 7018 electrodes. The weld joint configuration for 12 mm plate is shown in Figure 1. The 8 mm thick weld joint had the same configuration as the 12 mm joint. Since proper acoustic coupling between the ultrasonic probe and the test surface is very important, the weld crowns were machined flush with the base metal. Flat regions were also necessary for positioning the magnetic yoke for MAE studies. For XRD measurements, the measurement spots were electrochemically polished to avoid the influence of the machined layer on the measured data. Post weld annealing was carried out for the 8 mm and 12 mm thick plates at 873 K for two hours. After annealing the oxide scales were removed by using emery·papers and then measurements were carried out.

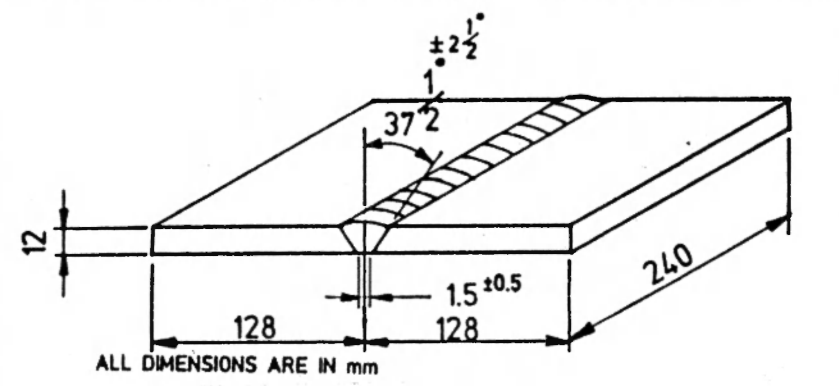


Fig 1 : Weld Design for 12 mm Thick Weld Joint

X-Ray Diffraction Technique for The measurement of Residual Stress.

The X-ray diffraction technique measures the interplannar spacing of the lattice to arrive at the stresses present in the material [3]. It is well known that peak intensity of diffracted x-ray beam occurs when bragg's law is satisfied.

$n\lambda = 2\,d.\sin\theta$

where, n = Order of difracton,

λ = Wave length of x-ray used.

d = Separations between a set parallel lattice planes,

θ = Angle of diffraction

In the presence of elastic macro stress there is a shift in the positions of the X-ray peaks. The difection of shift depends on the nature of the stress i.e. whether they are tensile or compressive. The magnitude of the shift gives a measure of the stress. Figure 2 shows the co-ordinate system relevant to the technique used. OA, OB and OC refer to the orthogonal directions relative to the sample surface. The directions OA and OB lie on the specimen surface. Directions OC is perpendicular to the specimen surface. The angle ψ denotes the angle of incidence of the X-ray beam. The direction of incidence CO denotes $\psi = 0$, and direction MO denotes $\psi = \psi$. Direction ON is the projection of OM on the specimen surface. The stress on the specimen surface oriented along ON is denoted as σ, where ϕ = the angle between OA and ON. The following equation is then valid :

$$\frac{d_{\varphi\psi}-d_0}{d_0} = \frac{1+r}{E}\cdot\sigma_\varphi - \frac{r}{E}\left(\sigma_{OA}+\sigma_{OB}\right)$$

where, E = Young's modulus

r = Polson's ratio

$\frac{E}{1+r}$ = Stress constant

$d\phi\Psi$ = Interplanner spacing measured in the direction described by the angies Ψ and ϕ

$d0$ = Stress free interplanner spacing.

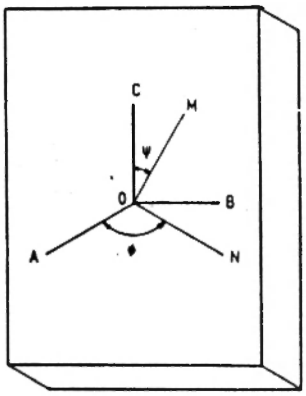


Fig 2 : Co-ordinate axes for XRD residual stress measurement

To an approximation $d0$ can be replaced by $d\varphi\Psi$ and to obtain the value of $\sigma\phi$, It is necessary to find the slope of equation (2). To achieve this, measurements of the changes in lattice plane separations is needed at $\Psi = 0$ and atleast at another value of Ψ , Stress, constant has been calculated using E=206.9 GPa and Poison's ratio of 0.29. In the present study Cr $K\alpha$ X-ray radiation was used and the 2θ values for the (211) planes were in the region of 156 degrees.

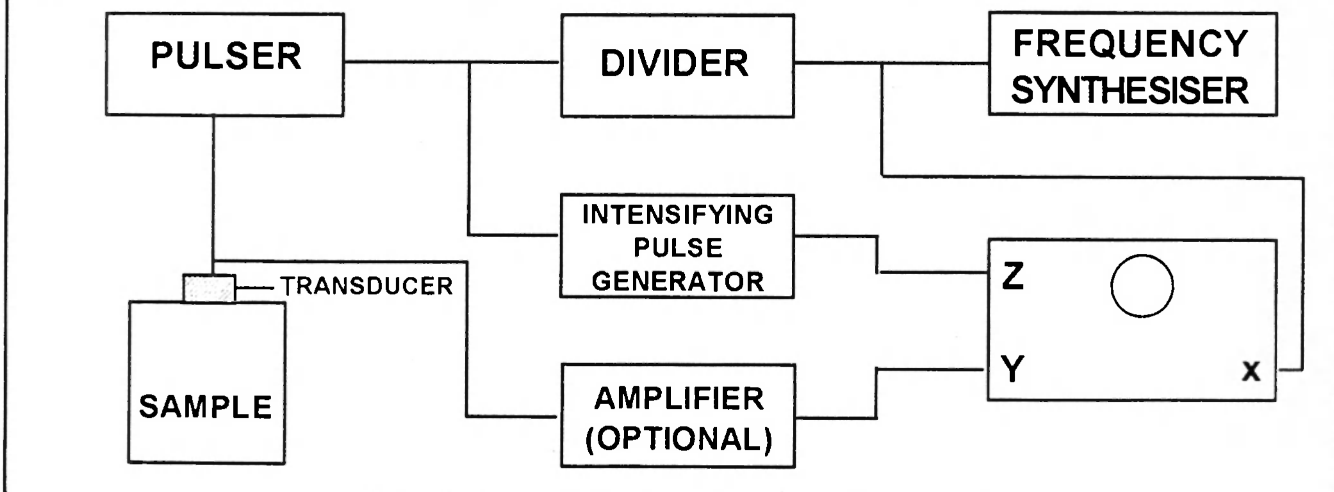
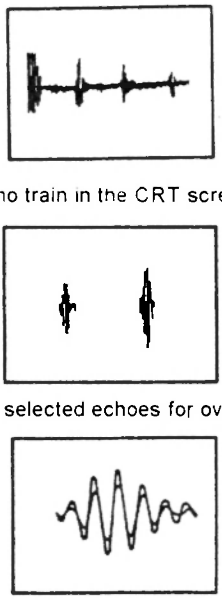


Fig 3 : Block diagram of the pulse - ECHO OVERLAP SYSTEM



i. Echo train in the CRT screen

ii. Two selected echoes for overlap

iii. overlap achieved by adjusting the CW frequency

Fig 4 : Sequency of overlap of any two echoes in ultrasonic velocity measurement

Ultrasonic Technique of Residual Stress Measurement

Stress measurements using ultrasonic technique are dependent on the acoustoelastic effect, i.e. strain-induced ultrasonic wave velocity variations. According to acoustoelastic theory, these variations behave linearly provided the material is deformed in the elastic range (4). The linear change in velocity which takes place due to stress change is very small and the percentage variation with applied or residual stresses does not exceed 1% in any situation. For the measurement of travel time, Pulse-echo overlap (PEO) method has been used with an accuracy of transit time measurement of the order of +1 nano second. The PEO method is a versatile and simple method that gives accurate measurement of ultrasonic travel time in materials [5]. Figure 3 shows the block diagram of the PEO set up developed in this centre and used in this work. The principle of measurement in this method is to make two successive back wall signals of interest to overlap in the oscilloscope screen by driving the X-axis with a carrier frequency whose period is the travel time between the signals of interest. Then one signal appears in one sweep of the oscilloscope, and the other signal appears in the next sweep. Figure 4 showing typical tracings obtained from the oscilloscope screen explains the principle of the method.

Acoustoelastic constant is defined by the following simplified equation :

$$V = V_0 + A\sigma \quad \text{............ 3}$$

where σ = Stress

V = Ultrasonic velocity in the material under stress

V_0 = Ultrasonic velocity in the stress free material

A - Acoustoelastic constant (AEC).

To find out the value of AEC, a flat tensile specimen of 8 mm thickness made from annealed mild steel plate was loaded by using an universal tensile testing machine. Starting from zero load and at various levels of increasing loads, ultrasonic velocity was measured through the thickness of the gauge length where uniform elongation occured. A krautkramer K2N 2MHz longitudinal beam probe was used. Figure 5 shows the percentage increase in the ultrasonic velocity as a function of stress in the specimen. From the stop of the straight line found by regression analysis, the value of AEC constant was determined to be 0.1167 m/MPa. Ultrasonic velocity measurements were carried out along a line perpendicular to the weld axis by using the same 2 MHz longitudinal wave probe. At each position, on an average a minimum of five measurements were carried out. Relative changes in the velocities were converted into respective RS values by using equation [3].

Magnetomechanical Acoustic Emission Technique for Residual Stress Determination

Magnetomechanical Acoustic Emission (MAE) is relatively a new technique [6]. It has potential application for microstructural characterisations and residual stress measurements. In presence of varying external magnetic field, the following domain related activities take place domain

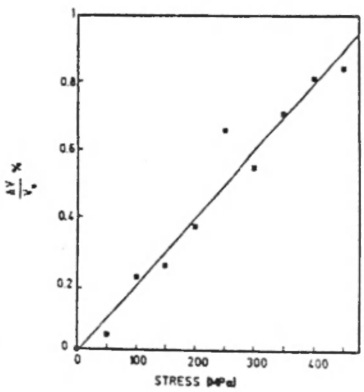


Fig 5 : Plot of velocity changes as a function of applied load in carbon steel plate nucleation, domain wall motion, domain rotation and domain annihilation. These activities take place so as to increase the net magnetic moment in the direction of the magnetic field. They are influenced by the microstructural features and applied and residual stress. There are two main types of domain walls - 180 degree and 90 degree. Signals are generated during the discrete jumps of the 180 degree domain walls from one set of obstacles to the next. This causes small discontinuities in the net magnetic moment which can be detected as transient pluses of emf in a coil placed nereby. This is known as Magnetic Barkhausen Noise (MBN) or BN. In addition to the 180 degree domain wall motions, there are changes in elastic energy due to magnetostriction during 90 degree domain wall motions. This results in the generation of elastic waves known MAE. The frequency spectrum of the MAE generally extends upto several hundred kHz. The maximum depth of the specimen which is active for the generation of MAE would depend on the frequency of the varying magnetic field. For a line frequency of 50Hz, the depth will be of the order of 1 mm. It has been found that both tensile and compressive stresses are found to decrease MAE(7). Therefore, in the present work, it has been taken that the sign of the stress does not affect the intensity of MAE. The set up used to carry out the experiments is shown in Figure 6. The line frequency current source (50 Hz) was used to produce the desired magnetic field. All measurements were done at a fixed coil current of 1 Amp. The corresponding magnetic field produced at the centre of the yoke was 400 oersted. Acoustic emission signals generated were recorded and analysed using an AET-5000 system. A plezoelectric transducer having a resonant frequency of 175 kHz, a preamplifier (60 dB gain) and the compatible filter (125-250 kHz) were used to capture the signal. The preamplified signal was further amplified by using the post-amplifier in the AET system. A total gain of 100 dB was used. The rms voltage of the amplified signal was used for the analysis. The yoke was moved in steps of 0.5 cm in the beginning upto 2 to 3cms from the weld centre line and then in steps of 1 cm and the rms voltage of the MAE signals were recorded at each position.

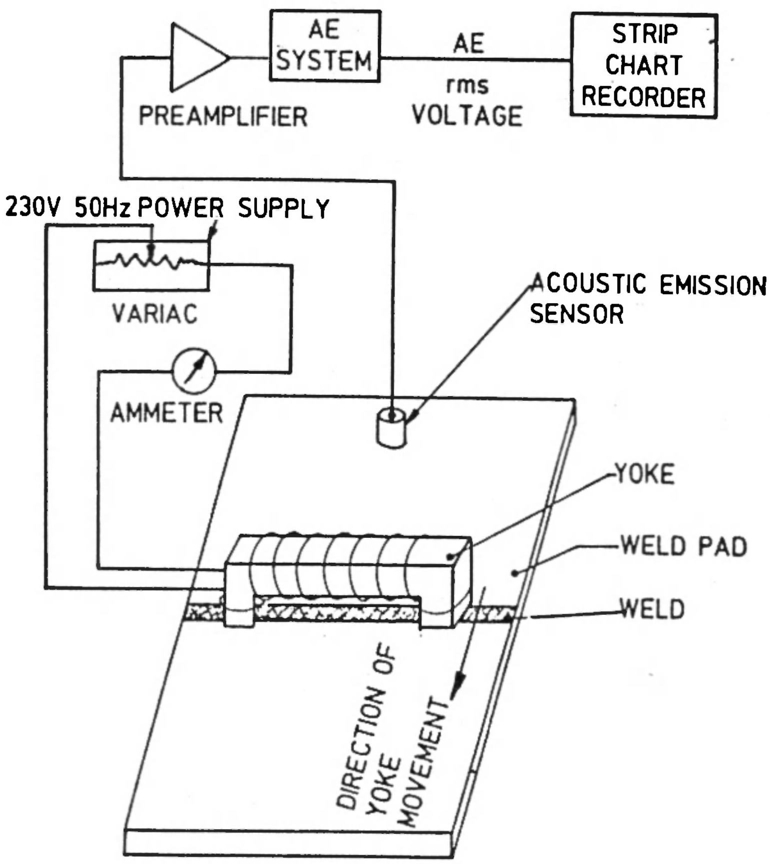


Fig 6 : Sketch showing set up for magnetomechanical Acoustic emission technique

Results from XRD Technique

Figure 7 shows the residual stress variation across the 8 mm thick weld joint. The measurements were done in directions along the weld line on the top surface of the plate. Figure 8 shows the variation when measured across the root pass. Figures 9 and 10 show the corresponding variations in 12 mm thick plates. The following observations can be made from these four figures : The stresses are tensile in the weld region with a maximum occuring at the weld centre line. From this maximum value at the centre line the tensile RS reduces and changes its nature to compressive RS in the heat affected zone (HAZ), in all the cases except in the 12mm thick plate in as welded condition when measured across the root pass (Figure 10). However in the case of 12 mm thick plate the stress across the root pass is seen to be still tensile at locations away from the centre line. This could be due to the fact that the 12 mm plate got distorted during welding giving rise to tensile RS at the bottom surface. This is corroborated by Figure 9 which shows that the parent metal regions in the as welded condition have a high level of compressive stress. For the 8 mm thick plate, the maximum tensile stress on the top surface is lower than that seen on the bottom surface. A reverse trend is observed in case of the 12 mm thick plate. The maximum tensile and the maximum compressive stresses in the 12 mm thick plate are higher than those in the 8 mm thick plate. It will be seen later that ultrasonic measurements give an opposite trend with 8 mm thick plates showing higher stresses. It can be rationalised by assuming that the restraints on the surface layer during welding are more when the thickness is increased.

Results from Ultrasonic Technique

Figure 11 shows the comparative RS distributions along the line perpendicular to the weld axis and on either of its side in the 8 mm and 12 mm thick weld pads. The RS patterns are averaged in the volume of the material through which the ultrasonic beam passes. Although the maximum tensile stress at the weld centre is similar for the two thick-

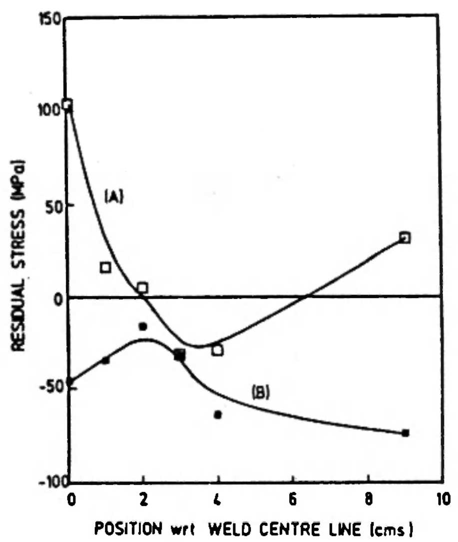


Fig 7 : XRD Residual stress
on top surface of 8mm Thick Weld Joint
(a) In as welded condition
(b) After annealing at 873 for 2 hrs.

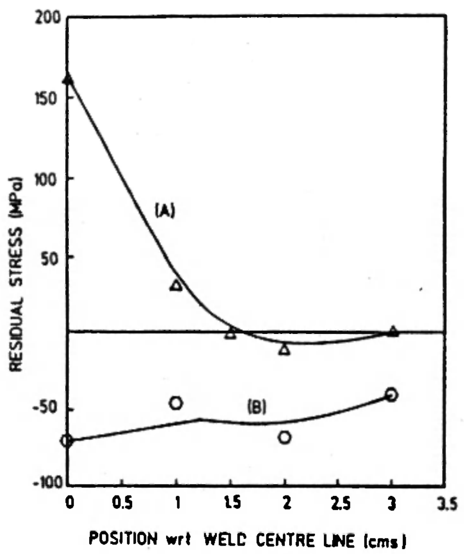


Fig 8 : XRD Residual stress accross
root pass in 8mm , Thick Weld Joint
(a) In as welded condition
(b) After annealing at 873 for 2 hrs

nesses, the compressive stress level in the HAZ region is comparatively lower in the 12 mm thick plate and higher in the 8 mm thick plate. This type of observation is opposite to what has been observed on the surface layer measured by XRD technique pointing to the possibility that the restaint effects in the thickness direction are not the same as what are present on the surface regions. Figure 12 shows the effect of annealing (at 873K for 2 hours) in the 8 mm thick plate. The stresses are significantly reduced by the annealing though the measured stresses are still not zero even after annealing at 873K. Figure 13 shows the effect of annealing in the 12 mm thick plate. Both the tensile and the compressive stresses are reduced in magnitudes.

Results from MAE

The variation in MAE rms voltage with distance from the weld centre line for unannealed and annealed weld pads of 12 mm and 8 mm thickness are shown in Figure 14. The MAE rms voltage is higher in annealed weld pads as compared to unannealed and weld pads. The extent of variation in the MAE rms voltage with distance from weld centre line is also reduced in the annealed weld pads as compared to the unannealed weld pads. Comparison of variation is residual stress as determined by the ultrasonic velocity measurements with the corresponding variation in MAE rms voltage suggests the following; Generally upto 2 to 3 cm from weld centre line, the stress is high in the unannealed weld pad. The MAE rms voltage is minimum at the weld centre line where the stress is maximum. Release of these stresses by annealing resulted in large increase in MAE rms voltage in this region. The continued increase in MAE rms voltage beyond 3 cm in the unannealed weld pads is attributed to the continued decrease in compressive RS (Figure 12). The rms voltage was found to saturate beyond 6 cm from weld centre line in the case of 12 mm weld pad as the stress reached a zero level.

CONCLUSIONS

In the preceding sections, the experimentally determined RS stress variations across butt weld joints in 8 mm and 12 mm thick mild steel plates, before and after

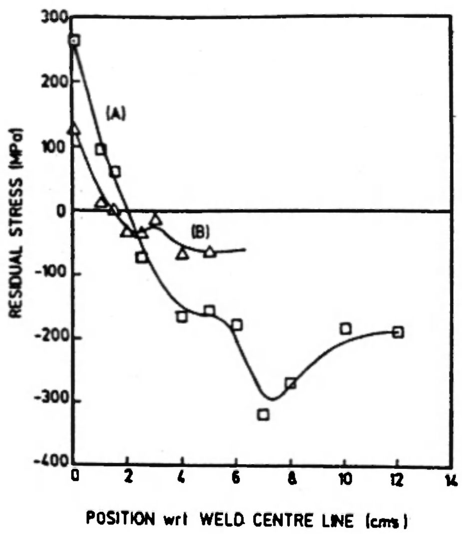


Fig 9 : XRD Residual stress on top surface of 12mm Thick Weld Joint
(a) In as welded condition
(b) After annealing at 873 for 2 hrs.

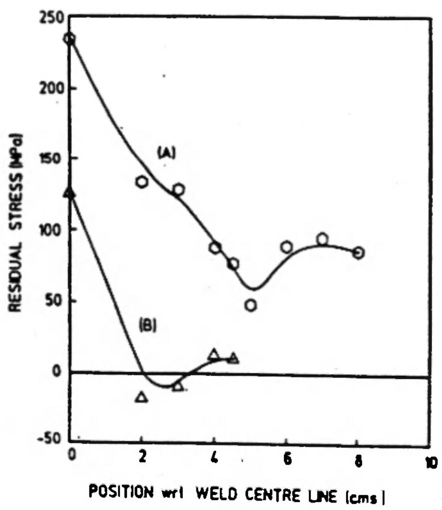


Fig 10 : XRD Residual stress accross root pass in 12mm , Thick Weld Joint
(a) In as welded condition
(b) After annealing at 873 for 2 hrs.

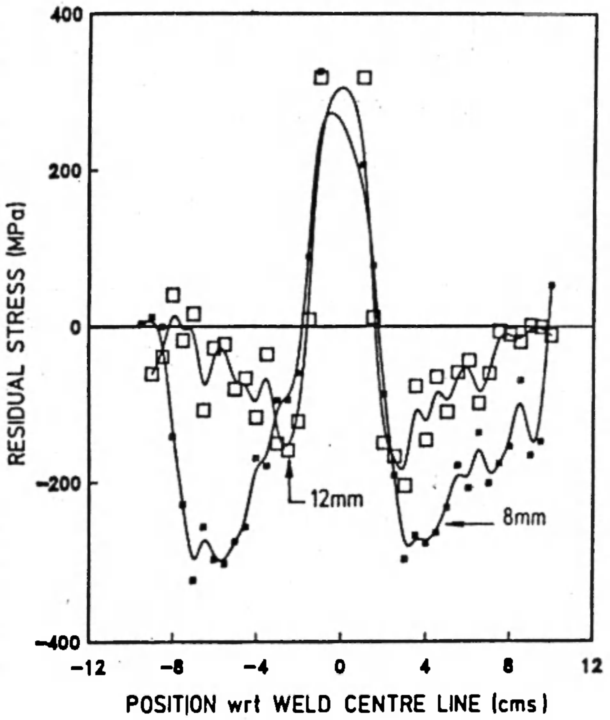


Fig 11 : Thickness Average Residual Stress variation measured by ultrasonic technique in as weldede 8mm and 12mm thick mild steel plates

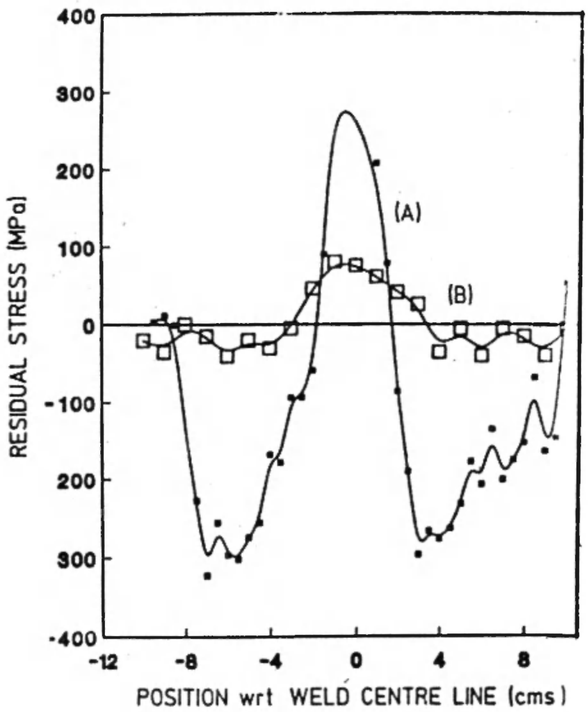


Fig 12 : Effect of annealing on the thickness Averaged Residual Stress measured by ultrasonic technique in 8mm thick plate.
(a) As welded (b) 873K Anneal

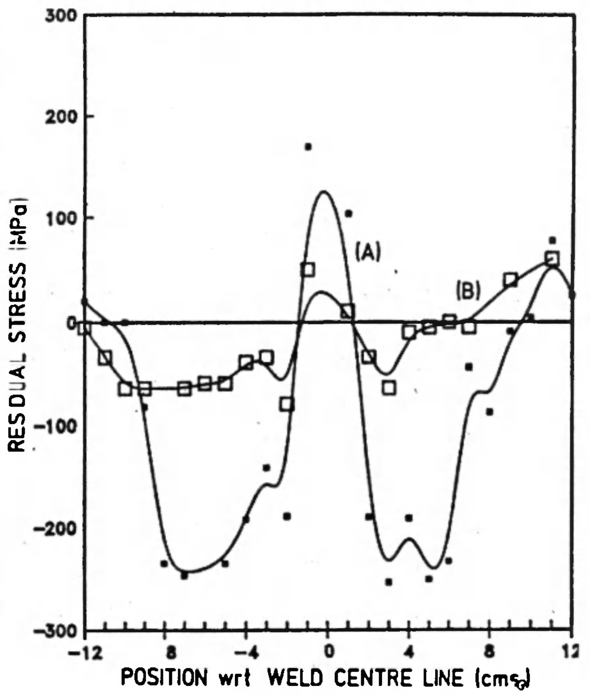


Fig 13 : Effect of annealing on the thickness Averaged Residual Stress measured by ultrasonic technique in 12mm thick plate.
(a) As welded (b) 873K Anneal

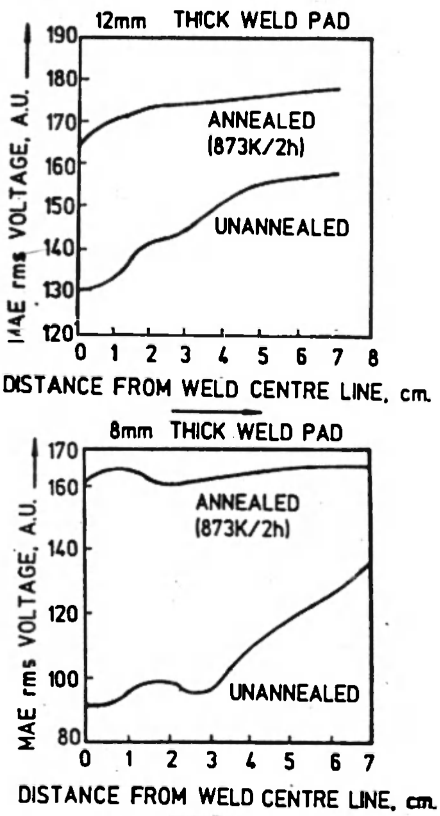


Fig 14 : Variation in MAE with distance from weld centre line annealing at 873K for two hours, were discussed. The XRD and the ultrasonic results show that the trends in the surface stress variations can be different from those occuring in the thickness direction. The MAE results have shown good corelation with respect to the effect of annealing and it can be used to monitor the effect of stress relief annealing.

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