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Measurement of Residual Stresses of DH32 Steel Plates in Different Welding Joints by Using Conventional Strain Gauges and FEA Methods

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Residual stresses are those stresses that remain in an object (in particular, in a welded component) even in the absence of external loading or thermal gradients. In some cases, residual stresses result in significant plastic deformation, leading to warping and distortion of an object. This paper investigates the prediction of residual stresses developed in shielded metal arc welding of high thickness DH32 (ASTM A131) steel plates through Finite Element Simulation and experiments. To evaluate the residual stresses in weldment, conventional strain gauges are used. These stresses are developed on the Butt joint and T joint. The geometry of the T joint and butt-welded Low Carbon Steel (ASTM A131) plates was modeled and the residual stresses were simulated using ANSYS V19.2. Sequentially coupled transient thermal-mechanical, three-dimensional finite element models were developed and the Element Birth and Death Technique was used in simulation to evaluate the stresses in simulation. The conventional strain gauges are placed in different weld zones and the obtained results from these gauges are different as per the FE results. These results show that the residual stresses obtained by prediction from the finite element method are in fair agreement with the experimental results. Based on this, it can be concluded that how far we can use the strain gauges used in the measurement of residual

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stresses. and also the Finite Element Model can be used to replicate and determine the expected residual stresses that would be generated before an actual welding process is carried out.

Keywords: Residual stresses; metallurgical process; DH32 steel; element birth; death technique; shielded metal arc welding process.

NOMENCLATURES

V = Output voltage
BV = Bridge excitation voltage
$\varepsilon = Strain$
$\sigma = Stress$
E = Youngs modulus

1. INTRODUCTION

DH 32 steel is one of high strength steel which is coming under the material ASTM A131 Category. This specification covers structural steel plates, shapes, bars, and rivets intended primarily for ship construction. The shapes and bars are normally available as Grades A, AH32, and AH36. When the steel is to be welded, it is presupposed that a welding procedure suitable for the grade of steel and intended use or service will be utilized [1] ASTM A131 DH32 shipbuilding steel is not only the high tensile strength steel but also is the Hull structural steel. DH 32 shipbuilding steel has good toughness properties, higher strength, strong corrosion-resistance, processing properties, and good welding properties. Shipbuilding is used for shipbuilding and oil platform purpose and they are approved by ABS. DNV, GL, BV, LR, NK, RINA, and other classification societies. What's more, DH 32 shipbuilding steel plate can be used in manufacturing the ship's hull structure whose weight is below 10000 tons [2].

Welding is defined by the American Welding Society (AWS) as a contained union of Metals or non-metals produced by either heating of the materials to a suitable temperature with or without the application of pressure, or by the application of pressure alone, with or without the use of filler metal [3]. Residual stress is defined as "the stress resident inside a component or structure after all applied forces have been removed" [4]. Compressive residual stress acts by pushing the material together, while tensile residual stress pulls the material apart. Residual stress effects are the following; distortion, Crack initiation, and propagation. (Damage tolerance), Peen forming (controlled distortion), Fretting. Stress corrosion cracking (SCC) and hydrogen-initiated cracking (HIC). Any of these effects if not checked is liable to cause failure during service. Thus, the need for a Finite element. method to predict the expected residual stresses.

For many plain carbon sheets of steel, such as A36, with thickness less than 19mm (3/4”), the maximum interpass temperature is not critical. EH36 is steel typically used for shipbuilding applications and the maximum interpass temperatures shall not exceed 200°C (392°F) for thicknesses up to 40 mm (11/2 in) inclusive, and 230°C (446°F) for greater thicknesses. For steel higher interpass temperatures will generally provide a finer grain structure and improved Charpy V notch toughness transition temperatures. However, when interpass temperatures exceed approximately 260°C (500°F), this trend may be reversed [5].

Gurinder [6] researched finite element simulation of residual stress in butt welding of two AISI 304 stainless steel plates using a finite element based commercially available software, coupled thermal-mechanical three-dimensional finite element model was developed by making an approximate geometry of the butt-welded joints. Jeyakumar, et al. [7] carried out a thermo-mechanical 3D finite element. analysis to assess the residual stresses in the butt weld joints of ASTM A36 steel plates utilizing the commercial software package ANSYS. Stamenkovic [8] performed a 3D residual stress analysis of butt-weld joint of ASTM 36 steel plates (100 x 100 x 3mm) with arc efficiency, n=0.85, arc voltage (V) 24 V, the current (1) = 180A, 3 mm and welding speed = 51 mm/sec. The peak temperature reached 1973K with tensile stresses were developed in the weld zone.

Li Yajiyang et al. [9], explored the distribution of residual stress in the gas shielded arc weld joint of HQ130 grade high strength steel using ANSYS software, and Andrea Capriccioli and Paolo Frosi [10] showed the usefulness of dynamic mesh in a large sensitivity analysis.

The finite element method (FEM) is a computational technique used to obtain approximate solutions of boundary value problems in engineering. The finite element method is a way of getting a numerical answer. to a specific problem. A simple description of FEM is the cutting of a structure into several elements, describing the behavior of each element merely, reconnecting the elements at "nodes as if it were pins or drops of glue that held the elements together [11].

2. EXPERIMENTAL AND METHODOLOGY

In this experiment, the residual stresses are developed in two types of joints those are Butt joint and T joint by using the material DH 32 steel plate. And the material is fully killed steel. The dimensions of the butt joint for each plate is 100 mm × 100 mm × 25mm and T joint for each plate is 100 mm × 100 mm × 12.5mm. The composition of this material is shown in Table 1. The welding process was specified for this material is Shielded Metal Arc Welding experiment was done by [12].

2.1 Specimen Preparation

The experiment was carried out on the butt joint and T joint. For butt joints, the thickness of plates is 25mm, so the penetration of weld material is low. To improve the penetration of welding, we used double V groove edge preparation for base metal with 70 degrees angle. For the T joint, 12.5mm thick material is used so it doesn't need any edge preparation. The mechanical properties of the DH32 steel plate as shown in the Table 2.

There are four strain gauges are placed in different weld zones in the base plate. In the butt joint, the four strain gauges are placed at 90mm, 70mm, 50mm, 30mm in the x-direction. In the T joint, the strain gauges are placed at 45mm, 35mm, 25mm, 15mm from the centerline of the base plate. Each strain gauge is connected to the Wheatstone bridge as unknown resistance separately. By using the potentiometer, the bridge gets balanced which means the output voltage will be zero. When the welding process starts, Internal stresses were developed. because of these stresses, the strain gauge changes its resistance then the Wheatstone bridge gets unbalanced and the output Voltage will also change. From this Voltage, we can measure internal Strain and Stress in that particular area. The stresses and strains are calculated from equations 1 and 2 [13]. The features and details of strain gauges that are used in this experiment are given in Table 3.

$$\mathrm{Strain}(\varepsilon) = \frac{4\mathrm{V}}{\mathrm{BV} \times \mathrm{GF}} \tag{1}$$

$$Stress(\sigma) = E\varepsilon \tag{2}$$

Using the shielded metal arc equipment and E6013 electrodes, the welding was carried out in a single pass that lasted for 30 seconds. Weld time is 20 seconds, the specimens were then allowed to cool down to room temperature. All welding precautions were taken into consideration during the specimen production to ensure the reduction of error. The welding parameters are shown in Table 4. After the welding process, the samples were cleaned with a wire brush to remove carbon deposits.

Table 1. Chemical composition of DH32 Steel

S.No.	Element	Composition %
1.	Carbon	0.18
2.	Manganese	0.9-1.6
3.	Nickel	0.4
4.	Copper	0.35
5.	Chromium	0.2
6.	Silicon	0.1-0.5
7.	Molybdenum	0.08
8.	Vanadium	0.05-0.1
9.	Phosphorous	0.04
10.	Sulphur	0.035
11.	Titanium	0.02
12.	Aluminum	0.015
13.	Calcium	0.0005

Table 2. Mechanical Properties of DH32 steel

Elastic Modulus, GPa	Shear Modulus, GPa	Elongation %	Poisson's Ratio	Tensile Strength, MPa	Yield Strength, MPa
200-210	82	14-22	0.29	440-590	315

Table 3. Strain gauge features

Features	Details
Gauge Factor	2.11±1%
Gauge Resistance	350±0.3 ohms
Gauge Length	3mm
Temperature Compensation	11×10^{-6}/□
Transverse Sensitivity	0.001%

Table 4. Welding parameters

Welding	Voltage (V)	Current (A)	Electrode diameter (mm)	No. of Passes	Travel speed mm/s
SMAW	25	90	3.142	1	1

2.2 Finite Element Analysis

In this study, the butt weld joint and T joint of two DH32 steel plates were modeled using ANSYS V19.2. To simulate these joints, the coupled analysis of Transient thermal and Static structural analysis.

Thermal analysis has been carried out using the 3D element SOLID70, an eight-node quadrilateral element with a single degree of freedom having a temperature at each node. Although the structural analysis has been carried out using the 3D element SOLID185, eight-node quadrilateral elements having three degrees of freedom at each node (translation in the nodal x, y, z directions). The mesh generated 15,701 nodes and 3168 elements in the butt joint. In the T joint, 29,617 nodes and 6032 elements were generated. The analysis was solved and residual stresses were generated by using the Element Birth and Death technique.

2.3 Element Birth and Death Technique

The material deposition is modelled using an element "birth and death" technique. To achieve the death element effect, the ANSYS code does not remove the element from the model. Instead, the weld elements are first deactivated by multiplying their stiffness by a huge reduction factor. Meanwhile, to obtain the birth element effect, the ANSYS program reactivates the death element by allowing its stiffness, element load, etc. return to its original values [14].

3. RESULTS AND DISCUSSION

3.1 Residual Stresses Measured from Experiment

The conventional strain gauges are attached to the base plate at different weld zones. While passing the electrode, strain gauges are detached from the base plate because of overheat in the welding process. In the butt joint, one gauge detached. In the T joint, two strain gauges are detached from the base plate. Now, we got the output voltages from the sensors are obtained only three in butt joint as well as two output voltages in T joints. The remaining voltages are calculated by using polynomial extrapolation. The strain gauges are used to calculate the strains of the base metal from output voltages by using Equation 1. From Equation 2, The residual stresses are calculated from Hooks law i.e., Equation 3. The elastic modulus for the DH32 steel is 201 GPa. Residual stresses are measured for both butt joint and T joint are separately at the different weld zones mentioned in Tables 5 and 6 respectively.

3.2 Residual Stresses Predicted from FEA

The measured residual stresses obtained from the experiment are evaluated with simulation predicted values at their respective places in the butt joint and T joint. Figs. 1 and 2 demonstrate the predicted and measured residual stress distribution in the base metals of the butt joint and T joint respectively. It is known from the figure that the numerical simulation results are in good agreement with the measured residual stress, which confirms the validity and feasibility of simulation results by using simulation software. From Figs. 1 and 2, the blue lines indicate that the values obtained from the experiment, and the other lines indicate the FEA results where the strain gauges are placed in the base metals and heat-affected zones.

Figs. 3 and 4 show the residual stresses where strain gauges are attached to the base plates of the butt joint and T joint individually. The predicted residual stresses in the butt joint are 14.71 MPa, 2.41 MPa, 2.89 MPa, and 2.82 MPa at the distance of 90mm, 70mm, 50mm, and 30mm from the weld line respectively. The predicted residual stresses in the T joint are 224.7 MPa, 56.96 MPa, 23.68 MPa, 14.34 MPa at the distance of 15mm, 25mm, 35mm, 45mm from the weld centerline.

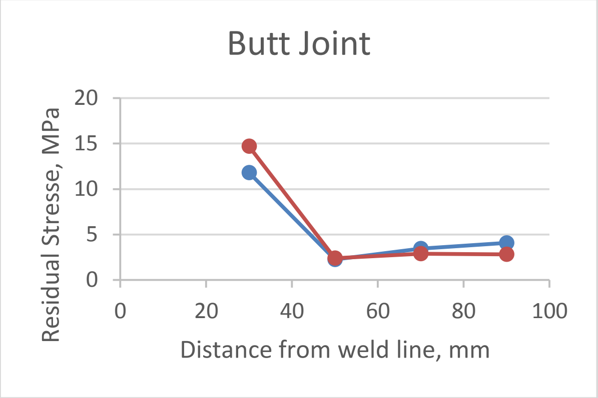

Fig. 1. Comparison of stresses in Butt joint

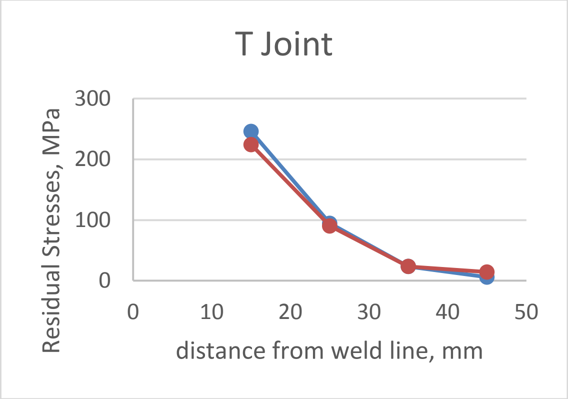

Fig. 2. comparison of stresses in T joint

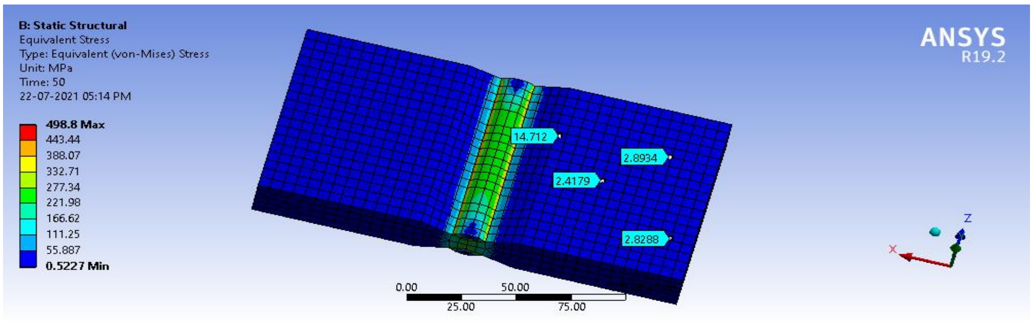

Fig. 3. Equivalent stresses where strain gauges placed in butt joint

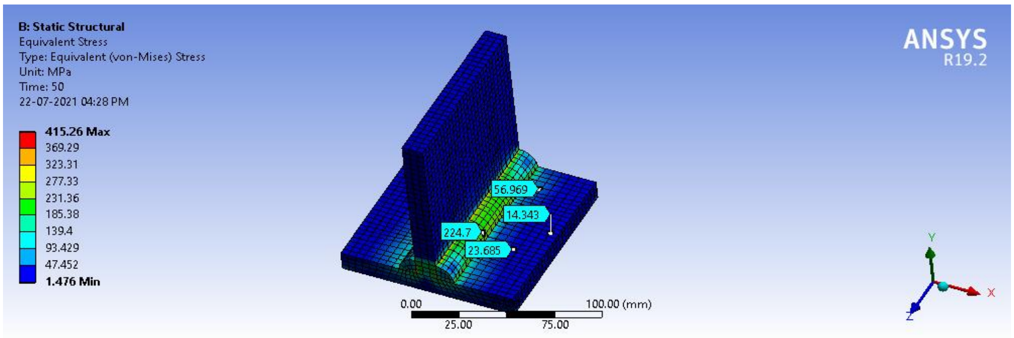

Fig. 4. Equivalent stresses where strain gauges placed in T joint

Table 5. Residual stress values in Experiment and simulation in Butt joint

Distance from weld line, mm	Experimental Stresses, MPa	FEA stresses, MPa
90	4.0786	2.8288
70	3.453	2.8934
50	2.259	2.4179
30	11.882	14.712

Table 6. Residual stress values in Experiment and simulation in T joint

Distance from weld line, mm	Experimental Stresses, MPa	FEA stresses, MPa
45	6	14.34
35	23.6	23.685
25	94.66	56.93
15	245.93	224.7

On the other hand, Fig. 5 shows the temperature distribution in the butt joint. The total weld cycle time is 50 seconds but the welding time is 20 seconds in both butt joint and T joint. The maximum temperature reached in the butt joint is up to 350℃. Fig. 6 shows the temperature distribution in the T joint. The maximum temperature obtained in the T joint is 228℃. The maximum temperature in the T joint is less than the butt joint because butt joint plates are high thickness plates.

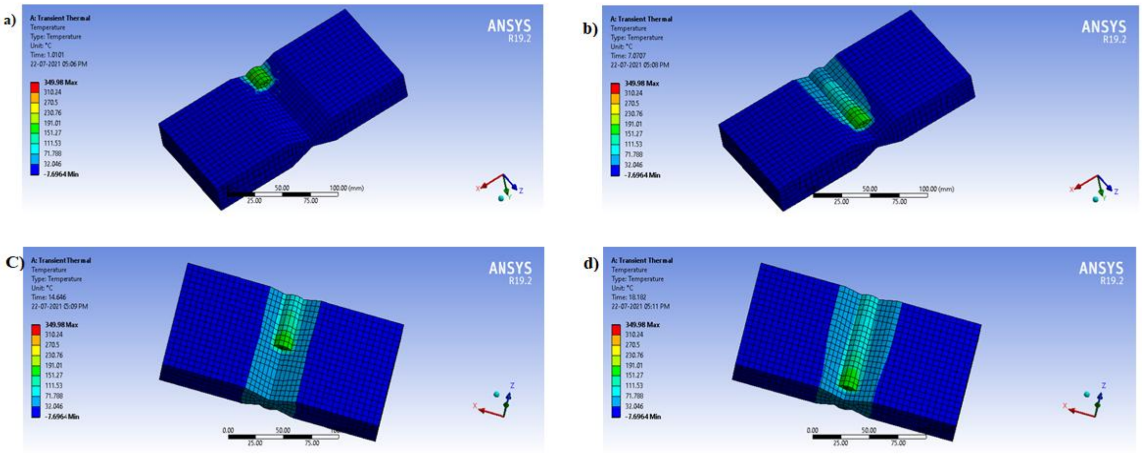

Fig. 5. Transient Temperature distribution in butt joint

a) Temperature distribution at time, t= 1 sec b) Temperature distribution at time, t= 7 sec
c) Temperature distribution at time, t= 14 sec d) Temperature distribution at time, t= 18 sec

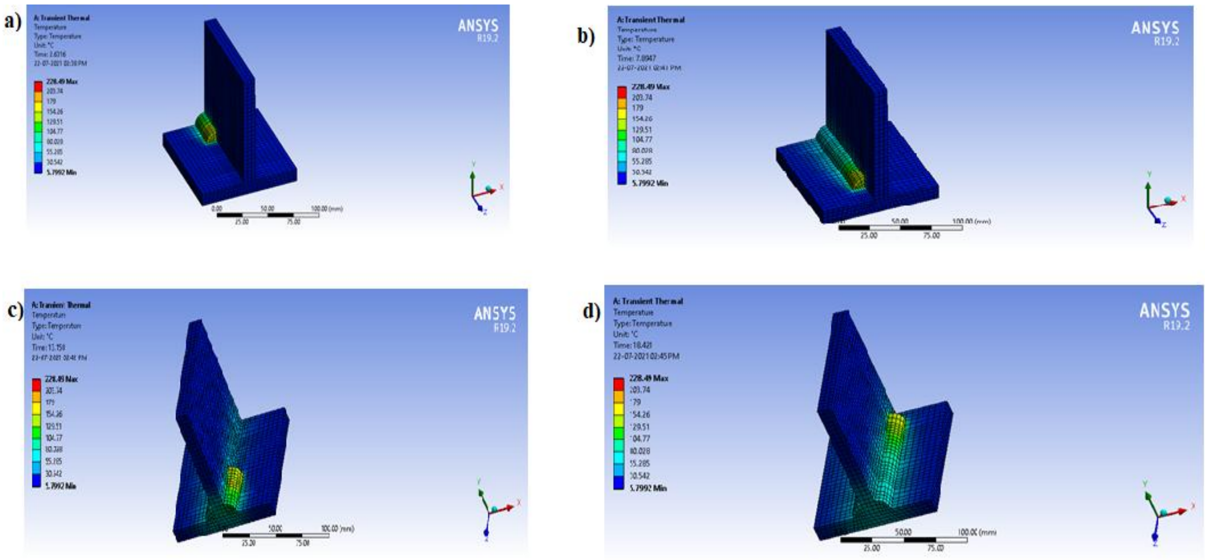

Fig. 6. Transient Temperature distribution in T joint

a) Temperature distribution at time, t= 2 sec b) Temperature distribution at time, t= 7 sec
C) Temperature distribution at time, t=13 sec d) Temperature distribution at time, t= 18 sec

From the Finite element simulation, we got the two types of residual stresses named Transverse residual stresses and Longitudinal residual stresses. Transverse residual stresses are the stresses which are acting in the normal to the x-direction(σ_x) and Longitudinal stresses are acting in the normal to the y-direction(σ_y). These stresses should be defined and calculated with respect to the weld line in the butt joint and T joint. Transverse stresses and Longitudinal stresses are calculated in the directions along the weld line and verticle to the weld line.

Figs. 7 - 8 show Residual stresses along the weld line are hat-like distribution. The maximum stress exhibits along the weld line are 559.9MPa and the minimum compressive stress is 339MPa. It can be seen from Figs. 7 and 8, the maximum transverse residual stress occurs at neat the weld line that is 255MPa at the middle portion of the weld line.

It can be seen from the results of Fig. 10, that the longitudinal residual stress of DH32 steel is distributed in a cap shape, the middle position in weldment along welding direction is tensile stress, and the two ends are compressive stress. The highest value of longitudinal residual stress is 160 MPa and the minimum value represents the compressive strength of the material. In addition, it can be found that the longitudinal residual stress has a maximum value in the middle portion of a weldment. Because, during the welding, when the welding heat source has not reached the middle of the weld, the base metal here is not subjected to the longitudinal directional stress. When the welding heat source moves here, the base material near the weld is subjected to longitudinal compressive stress. When the welding heat source is far away from here, the material shrinkage at cooling is subjected to the tensile stress given at both ends of a weldment. Therefore, the area near the weld experiences the variation process of compressive and tensile stress, which finally exceeds the yield strength of the material. As shown in Fig. 9, the longitudinal residual stress near the weld zone is 400 MPa. With the increase in the distance, the original tensile stress is transformed into compressive stress, and the compressive stress is up to -70 MPa, and then moved away from the weld, the longitudinal residual stress gradually changes to zero, indicating that in the welding process, the heat effect near the weld area is large, the thermal expansion is large, and the shrinkage effect is large at cooling. On the contrary, the effect far away from the weld area is small. In addition, the longitudinal residual stress near the weld is large, while the residual stress far away from the weld is relatively small, which is also related to the large thermal stress generated by the uneven temperature field during cooling.

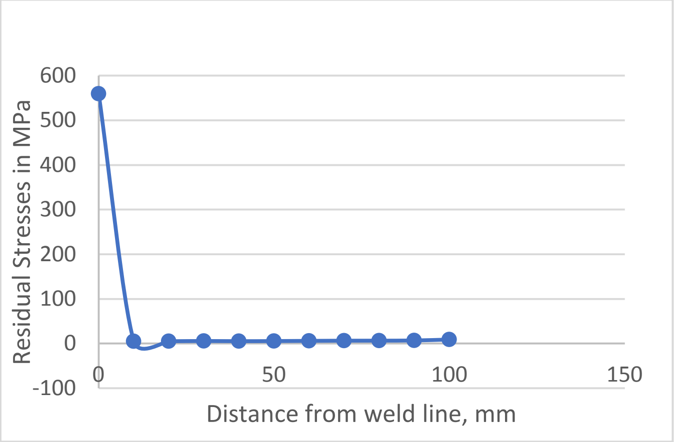

Fig. 7. Transverse Stress Distribution vertical to the weld line in Butt joint

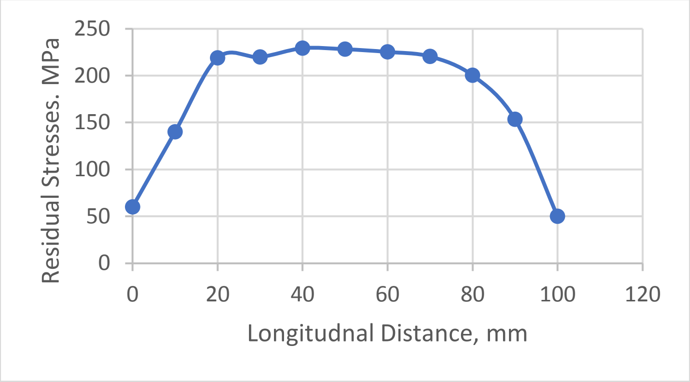

Fig. 8. Transverse stresses along weld direction in butt joint

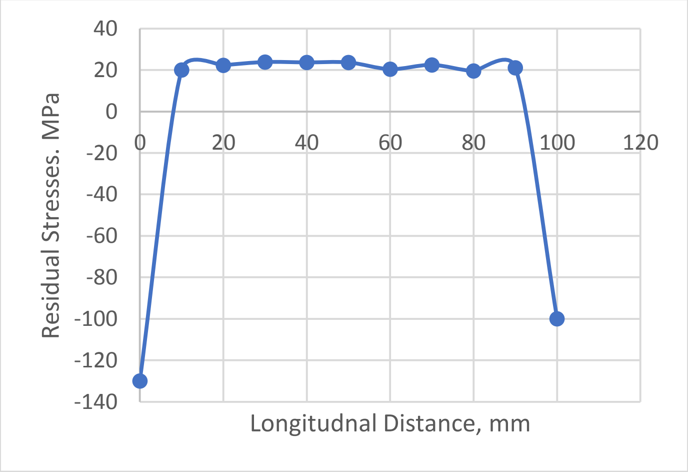

Fig. 9. Longitudinal Stresses along weld direction in butt joint

From Figs. 11-12 we can observe the distribution of Transverse residual stresses in the T joint. From Fig. 11, it can be seen that the transverse residual stress also exhibits a hat-like distribution in which the maximum transverse stress occurs at both ends of the cap edge and shows the tensile stress, which is approximately 280 MPa, and the compressive stress at both ends is about 260 MPa. It can be seen from Fig. 14, that the maximum transverse residual stress near the weld is about 250 MPa in the vertical weld direction, and at far away from the weld, the stress value tends to zero, and the stress is all tensile stress. In addition, it is found by comparison that the transverse residual stress is significantly lower than the longitudinal residual stress.

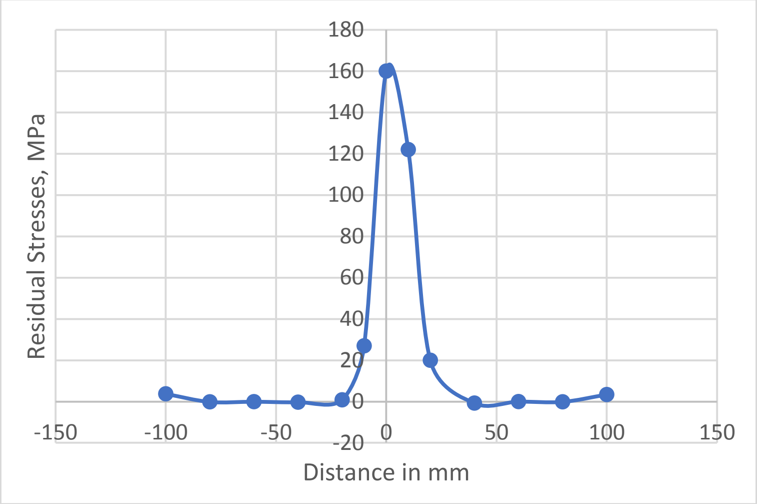

Fig. 10. Longitudinal Stresses vertical to the weld line in butt joint

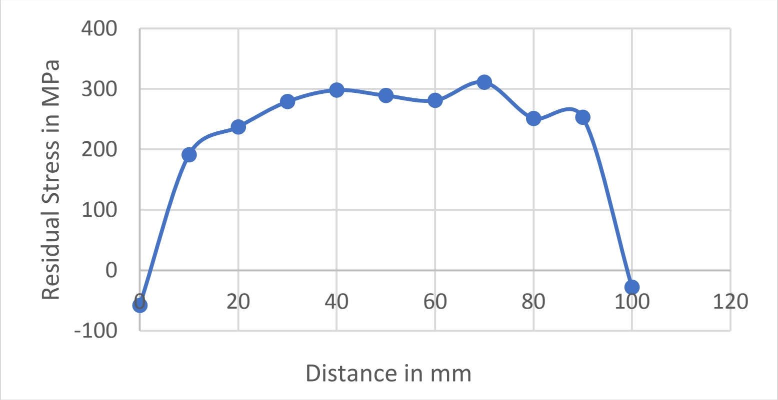

Fig. 11. Transverse residual stresses along weld line in T joint

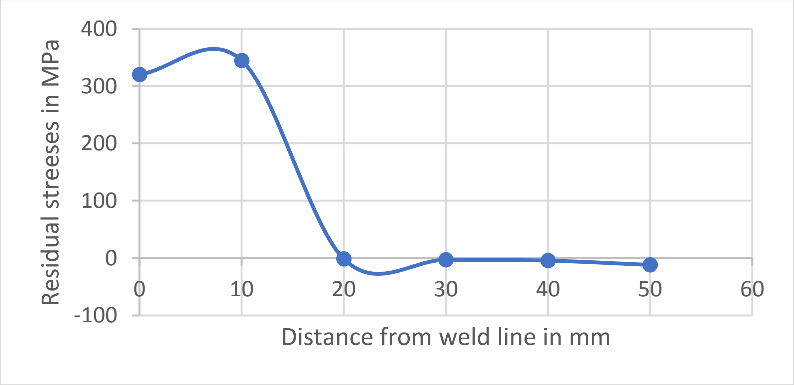

Fig. 12. Transverse residual stresses vertical to the weld line in T joint

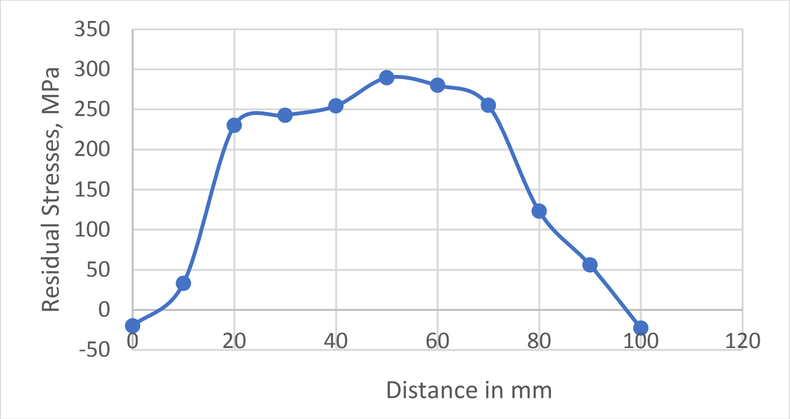

Fig. 13. Longitudinal stresses along weld line in T joint

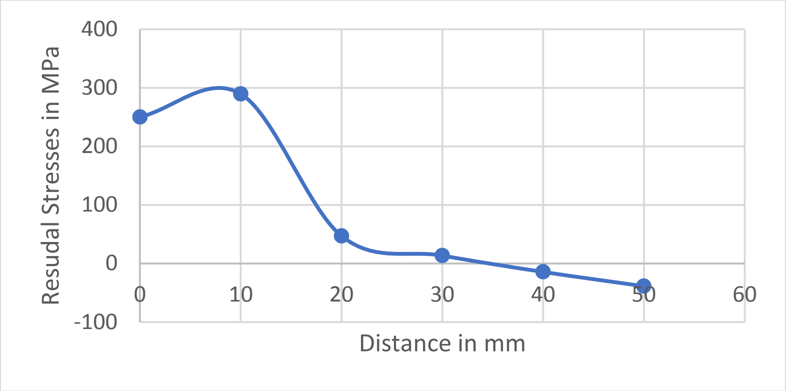

Fig. 14. Longitudinal stresses vertical to the weld line in T joint

4. CONCLUSION

In this paper, the temperature field and the residual stress distribution of DH32 steel T-type and Butt joint single-pass welding have been measured by using conventional strain gauges. To evaluate the experimental results, the residual stresses and temperature distribution are predicted in Finite Element Analysis. By using the Element birth and death technique in the FE model the results of residual stresses and temperature distribution results are got accurately. The Transverse and Longitudinal residual stresses are not much more than the yield strength of the material in both butt joint and T joint. The results of residual stresses showed that both transverse and longitudinal residual stresses reached peak values only near the weld region. Away far from the weld zone, residual stresses decreased to negligible values. The experimental residual stresses for both butt joint and T joint are in good agreement with FEA results only at base plate but not in HAZ because of its high temperature, the strain gauge limits exceeded. It was found that the conventional strain gauges can measure only in low-temperature conditions.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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