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Residual Stress and Distortion Analysis of a Welded Plate: Finite Elements Analysis

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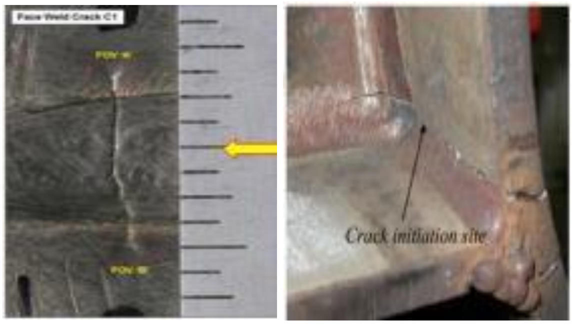
I. INTRODUCTION

Offshore structures are widely used to produce renewable and non-renewable energies. Welding is used to join majority of components in offshore structures to obtain higher strength in joint connection, ease of fabrication facility, and productivity. Fusion welding is the most used welding process to join oil and gas production, transportation facility, ship construction, and wind power generation. It is employed in the construction of jackets, tension leg platforms, guyed towers, stiffened and curved panels in oil and gas and so on.

With the onset of the new industrial era, offshore industries focus on minimizing the cost of energy production, transportation and increasing the service life of structures. The service life of structures can be improved by using advanced materials and technology for fabrication and ensuring higher quality by meeting the relevant codes and standards. As offshore facilities are subjected to highly dynamic and harsh marine environments such as wind waves, significant pressures, etc., it is essential to either eliminate or reduce the problems associated with the proper operation of structures. Structural welds under continuous, highly fluctuating loading often fail due to fatigue. One of the main issues in offshore construction is residual stresses during manufacturing and fabrication, leading to distortion issues. Residual stress and distortions highly influence the integrity of welded structures and affect the service life of components. Weld-induced residual stress can increase the chances of brittle fracture, decrease the buckling strength, elevate the stress corrosion cracking issues and reduce the fatigue life. Formation of transverse crack (Figure 1a) corner cracks (Figure 1b), and defects as a result of longitudinal residual stress, and buckling distortions in lightweight ship structure (Figure 1c) are illustrative examples of issues in welding science [1]. Cold cracking in steel due to hydrogen embrittlement in some welded steel is another issue of residual stress due to welding. The distortion caused by welding can result in dimensional inaccuracies resulting in misfits, which means more time needed during fabrication, incurring higher costs. Therefore, analysis of the residual stresses and distortions are critical in improving weldment performance, i.e., the structure's service life.



(a) (b)

. (c)

Figure 1: (a) Transverse crack in Titanium due to butt welding, (b) Corner cracks in FPSO unit [1], (c) Large buckling distortion [2].

II. RESIDUAL STRESSES AND DISTORTIONS

Stress can arise from various sources. Mechanical sources can either be internal or external. Examples of the external forces are wind, earthquakes, the weight of vehicles, people on bridges, etc. The internal forces, which are also called inertial forces, are caused only by the object's weight. The thermal source is the temperature gradient present/applied in a component, leading to thermal stress or thermally induced stress [3]. The stress present in an element can either be reaction stress or residual stress. Reaction stress represents the "overall distribution of tensile and compressive stresses" [4]. The stress left in a component (locked in stress) after removing an external source causing the stress is referred to as residual stress. The residual stress caused by an unbalanced strain, a by-product of a different process which the material is going through, is unsymmetrical in three orthogonal directions to the weld because of various restraints acting in each direction [5]. It may be desirable or harmful depending upon the application and the state of the stress. For instance, the tensile residual stresses on the surface of the objects are most often detrimental. These stresses can influence the formation of brittle-fractures. However, compressive stresses at the surface usually increase the component's fatigue strength [6]. Structural failure may occur even at lower levels of stress by buckling, caused by compressive stress. The probability of failure is higher in the presence of residual stress and distortions [7]. The tensile and compressive residual stress distributions in a butt-welded plate are shown in Figure 2.

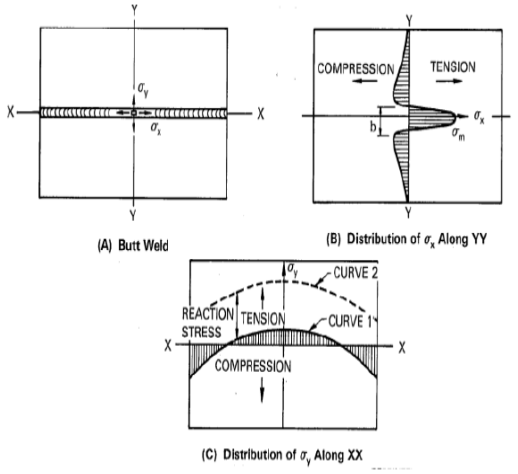


Figure 2: Distribution of residual stresses [7].

Welding distortion can be in-plane or out-of-plane. Rotational, transverse, and longitudinal distortion are considered in-plane distortion while buckling, angular, and longitudinal bending are considered out-of-plane distortion [8, 9]. Thermally induced stress distorts the material macroscopically or microscopically by yielding or cracking, elsewise resulting in residual stress as shown in Figure 2 and Figure 3. Microscopic distortion, in this case, can relieve the thermal stresses by creep [3]. Unbalanced stresses in weld produce longitudinal and transverse shrinkage along with angular distortions.

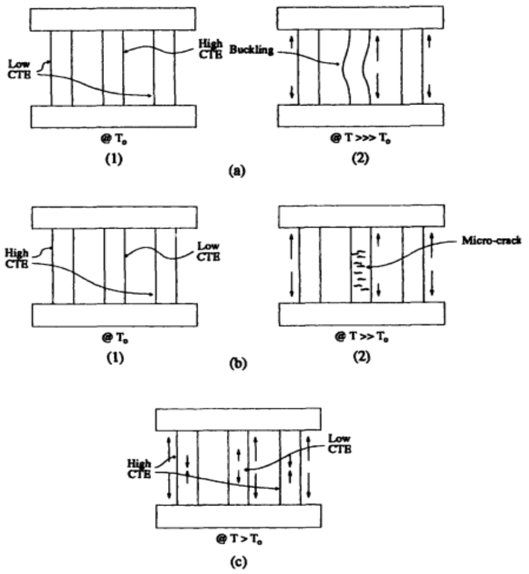


Figure 3: Thermal stresses resulting in (a) macroscopic distortions, (b) microscopic distortions, or (c) residual stresses [3].

A. *Residual Stresses due to Mechanical Operations and Machining Processes*

A mechanical operation such as rolling, extrusion, forming, forging, and so on and machining operation like grinding, milling, turning causes non-uniform plastic deformation in the material resulting in residual stresses [3, 10]. Mechanical operations initiate the residual stresses and are redistributed with an increase in magnitude during the machining process resulting in deflections, overcuts, and undercuts in the workpiece [10]. Initial residual stresses are considered the first order, which causes secondary order residual stresses during machining operations [11].

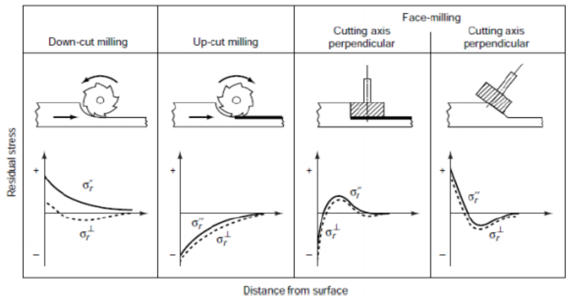


Figure 4: Variation of residual stresses in different milling operations [12].

B. *Residual Stresses from Welding*

Inherent problem of welding is that it can lead to the evolution of welding residual stresses, shrinkage, and distortion in the weldment and nearby areas in addition to the microstructural variation [13]. The residual stresses in the welding process can be induced by (a) volumetric changes relating to some change of phase, (b) difference in coefficient of thermal expansion of the joining material, and (c) temperature gradient leading to differential expansion (in the heating cycle) and contraction (in the cooling cycle). Due to the volumetric change of the same material in a different state (liquid, solid, gaseous), the material can have locked-in stresses. Suppose the joining material has a different thermal expansion coefficient. In that case, the material expands or contracts at different rates at the same temperature, resulting in uneven expansion and contraction, resulting in locked-in stresses. The residual stresses in weldment can arise because of restraint action experienced by weld metal due to temperature gradient. The difference in temperature at various locations gives rise to a different rate of expansion and contraction, thereby altering the dimensions and producing residual stresses [3].

As there is growing use of additive manufacturing processes in industries, there are broader areas to explore residual stresses in additive manufacturing. Wire and arc additive manufacturing produce a larger grain size and higher residual stresses and distortions. High-pressure rolling can be employed in such parts to alleviate the residual stresses [14]. The rapid heating and cooling cycle in the additive manufacturing process generates residual stresses analogous to the welding process [15].

III. RESIDUAL STRESS MEASUREMENT METHODS

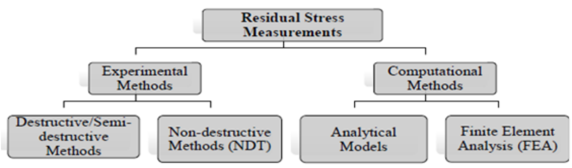


Figure 5: Residual stress measurement methods

Computational modelling requires less cost than establishing a laboratory setup for the experimental residual stress measurement limited by size, complexity, and accessibility. For example, the large structural components such as wind vanes cannot be tested if it poses a small crack under challenging locations. In such cases, analytical, and numerical methods are suitable. However, it does not eliminate the experimental test requirement but can be useful to examine and visualize the process as it evolves. The solution from the finite element model observations is validated with an experimental result that helps analyze and obtain the optimal parameters for the process.

A. *Finite Element Method to Predict Weld Induced Residual Stresses and Distortions*

In welding, the material properties such as thermal conductivity, heat capacity, elastic modulus, yield stress, and Poisson's ratio vary sensitively with temperature as the temperature change ranges from atmospheric temperature to melting point temperature of the metal (Paik and Technology, 2018). The thermal transition period leads to the phase change of metal from solid-Liquid-solid, leading to a change in material properties and specific volume. Therefore, it is challenging to obtain an analytical solution of stresses and temperature fields. The recent advancement of finite element analysis tools can provide detailed information on transition temperature, displacement, strain, and stress. The temperature-dependent properties can be stated, and properties such as phase change and the welding state can be modelled.

The use of simulation and the tests enables the evaluation of residual stresses that affect the life of the welded structure and the deformations that may hinder the functionality of the component (Lindgren, 2007). Finite element analysis is the most popular computational method in industries and the researcher's community to assess residual stresses.

The literature showed that axisymmetric and complete 2D models could provide acceptable residual stresses and temperature results with a drastic reduction in computational time. Therefore, using 2D thermo-elastic plastic FEA with appropriate assumptions can yield approximate results; hence, it is still widely used to analyze residual stresses and distortions.

1) Thermal Analysis

Thermal analysis is used to find the temperature value at each node of the mesh. The heat transfer in welded plate follows Fourier's law of heat conduction which states that the transient temperature field is function of space (x, y,z) and time (t) [16].

$$\nabla(k\nabla T) + \dot{q} - \rho c T = 0 \quad \text{..................... Eq. 1}$$

Above expression can also be written as

$$k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + Qv = \rho c_p \frac{\partial T}{\partial t} \quad \text{............ Eq. 2}$$

Where, Qv is volumetric heat flux, k is the thermal conductivity as a function of temperature, Cp(T) indicates the specific heat, and ρ is density of weld plate.

Newton's law of cooling is applicable for considering convection effects and Stefan-Boltzmann law is appropriate for considering radiative losses from the surface of welded plate.

$$q_c = h(T - T_0) \quad \text{........................ Eq. 3}$$

$$q_{rad} = \varepsilon\sigma(T^4 - T_0^4) \quad \text{.................. Eq. 4}$$

Where, h is convective heat transfer coefficient. T is temperature of welded plate and T_0 is ambient temperature, ε is emissivity, and σ is Stefan-Boltzmann constant.

2) Mechanical Analysis

The mechanical analysis follows fundamental principles of thermal-elastic-plastic equations. The mechanical analysis includes requires thermal narratives anticipated by the past thermal investigation for each time increase as a piece of information (thermal loading) to compute residual thermal stress and transient appropriations. The welded part gets strained as a result of heating and cooling cycles introduced by welding process which develops residual stresses and distortions. The total strain is sum of elastic strain (ε_e), plastic strain (ε_p), thermal strain (ε_T), volumetric strain (ε_V), and transformation-induced plastic strain (ε_{Ph}).

$$\varepsilon_{total} = \varepsilon_e + \varepsilon_p + \varepsilon_T + \varepsilon_v + \varepsilon_{Ph} \quad \text{............... Eq. 5}$$

Generalized Hook's law for an isotropic material is used to corelate the stress and strain. The plastic deformation resulted from thermal cycles is associated to Von mises criterion and can be used to calculate equivalent stress which is given in equation below [17].

$$\sigma_{\overline{D}} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \quad \text{...... Eq. 6}$$

Where, $\sigma 1$, $\sigma 2$, and $\sigma 3$ are the values of principal stresses.

IV. CASE STUDY: THERMO-MECHANICAL ANALYSIS USING FEM IN ABAQUS

A. *Model Geometry, Material Properties, Boundary conditions, and Assumptions*

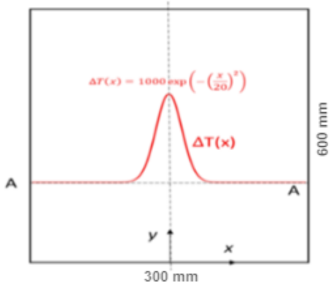


Figure 6: Full-size 2D axisymmetric model of the plate. The center axis line (y-axis line) is supposed as a welding line.

Table 1: Material Properties, BC, and Assumptions

Material Properties	***Boundary Conditions (BC)***	***Assumptions***
Low carbon steel material	X-axis: "YSYMM (U2 = UR1 = UR3 = 0) Y- axis: XSYMM (U1 = UR2 = UR3 = 0)	No hardening
Young's Modulus: E=206 GPa		Rate independent plastic properties
Yield stress SY=206 MPa, Poison's ratio 0.3		Phase Transformation effects are not considered
Thermal expansion Coeff.: 0.0000147 mm/mm/°C.	Equation $T(x) = 1000\exp\left(-\left(\frac{x}{20}\right)^2\right)$ The same temperature distribution is assumed to be constant along the plate length direction (i.e., y).	

B. Modelling and Analysis Procedure

Figure 7 shows the steps followed to perform finite element analysis of axis-symmetric plate.

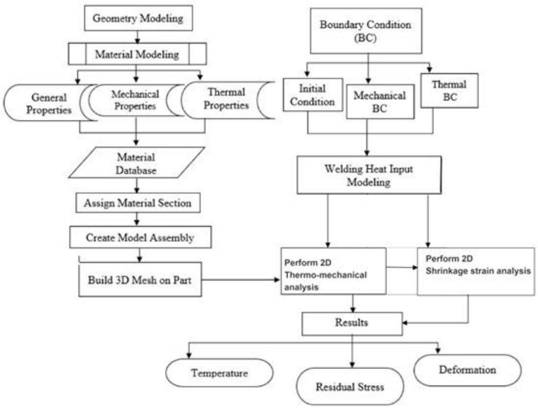


Figure 7: Flow diagram of thermo-mechanical and shrinkage Analysis[17].

V. RESULT AND DISCUSSION

A. Stress Vs. Distance Along and Across The Weld Centerline

Figure 8 shows the comparison of residual stress value (S11) obtained from thermo-mechanical and shrinkage strain method along the welding centerline.

Shrinkage strain method predicts that S11 component of residual stress increases very slowly along the welding direction till 225 mm, decreases steeply, and reaches a compressive yield strength value at the end (weld stop position) of the weld centerline. However, thermo-mechanical analysis shows that the S11 component of residual stress increases linearly and reaches a maximum value at 237 mm from the weld start position. At this point, there is a slight discrepancy in the residual stress obtained from these two methods. Thermo-mechanical study shows a higher value of tensile residual stress than shrinkage strain method. Finally, the shrinkage strain method also yields approximately the same value of compressive residual stress at the weld stop position.

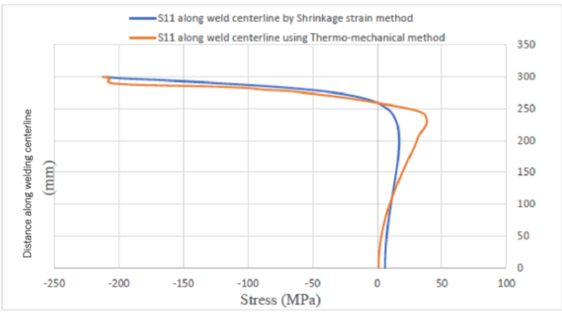


Figure 8: Comparison of S11 component of residual stress along the welding centerline from thermo-mechanical method and shrinkage strain method.

The transverse residual stress component (S11) along the welding centerline measured using thermo-mechanical study differs from the result obtained from shrinkage strain method at the beginning, which is shown in Figure 9. Although the distance across the welding centerline increases, the transverse residual stress value decreases, and the value obtained from both methods gets closer. Finally, the S11 component of transverse residual stress ceases to zero at the plate's bottom-right edge.

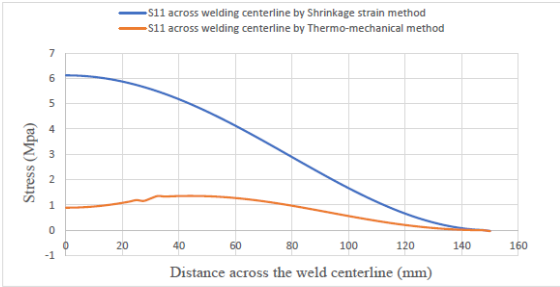


Figure 9: Comparison of S11 component of residual stress along the welding centerline from thermo-mechanical method and shrinkage strain method.

The second component of the residual stress (S22) is plotted across the welding centerline in Figure 10 using thermo-mechanical and shrinkage strain method. In the figure, from *zero* to 20 mm distance across the welding centerline, S22 values are close to yield stress value. Whereas there is a sharp decline of residual stress in the interval of ca. 20 - 30 mm. Furthermore, after 30 mm across the welding centerline, S22 flatten out and remain constant over the width of the plate.

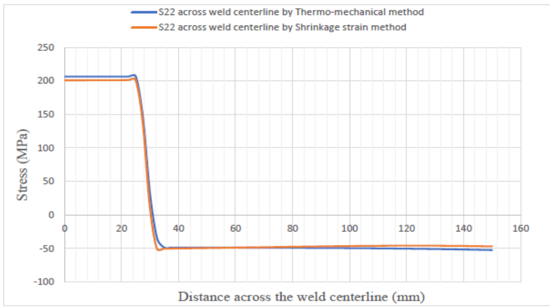


Figure 10: Comparison of S22 component of residual stress across the welding centerline from thermo-mechanical method and shrinkage strain method.

Figure 11 shows the variation of the S22 component of residual stress along the welding axis. As per thermo-mechanical analysis, yield level residual stress is generated initially, which slowly increases and reaches a maximum value of 222.35 MPa at 235 mm distance along the length of the plate. Then the value of residual stress decreases steeply over the remaining length of the plate and finally reaches a negligible value of compressive. The shrinkage strain method yields a slightly lesser tensile residual stress value than the thermo-mechanical method, measured along the weld direction initially. However, the difference in values obtained from both the study increases as the distance increases from the weld starts position till 250 mm, although the gap is reduced afterwards and finally reaches a similar compressive residual stress value.

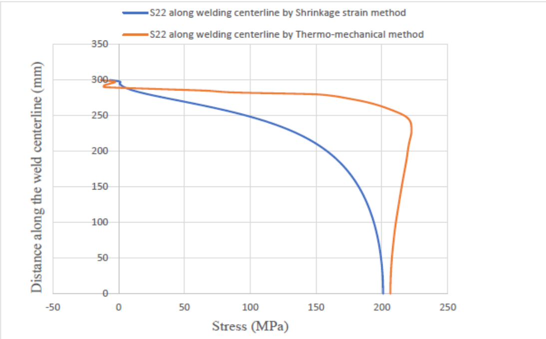


Figure 11: Comparison of S22 component of residual stress along the welding centerline from thermo-mechanical method and shrinkage strain method.

B. Displacement Contour Plot Comparison

Figure **12** (a), (b) shows displacement contour plots obtained from thermo-mechanical method. In the figure, U1 and U2 component of deformation indicates longitudinal shrinkage along welding centerline whereas positive deformation occurs across the width of the plate.

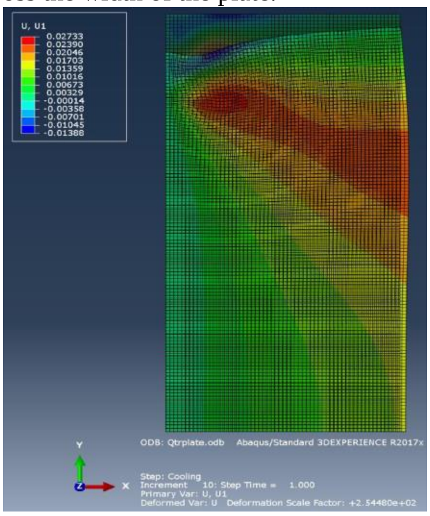


Figure 12 (a) Displacement contour plots along and across the weld centerline using the thermo-mechanical method. (a) U1 represents longitudinal shrinkage along the length of the welding centerline

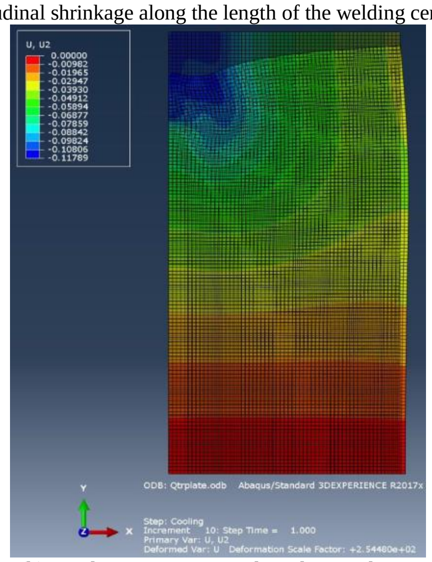


Figure 12: (b) Displacement contour plots along and across the weld centerline using the thermo-mechanical method. U2 describes transverse shrinkage across the welding line.

Figure 14 (a), (b) shows displacement contour plots obtained from shrinkage strain method. This method showed the shrinkage along and across the welding centerline of the plate.

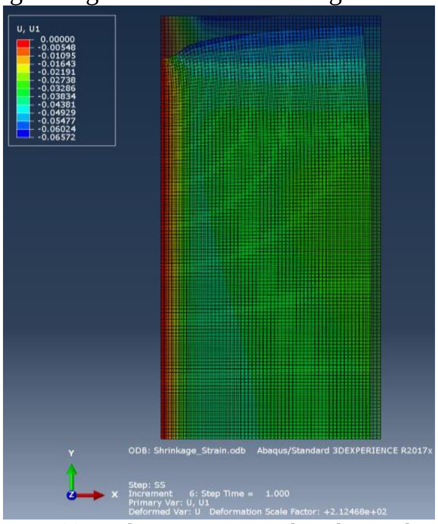


Figure 13: (a) Displacement contour plots along and across the weld centerline using shrinkage strain method. U1 represents longitudinal shrinkage along the length of the welding centerline.

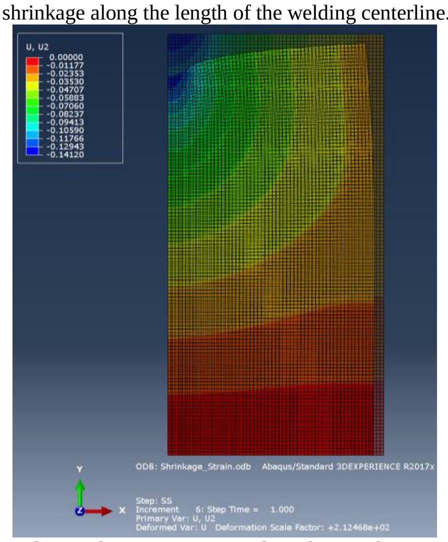


Figure 14: (b) Displacement contour plots along and across the weld centerline using shrinkage strain method. U2 describes transverse shrinkage across the welding line.

VI. CONCLUSION

Weld subjected to high restraint conditions experiences residual stress in longitudinal and transverse directions. Thermo-mechanical analysis and shrinkage strain method was also used to analyze the transverse and longitudinal stresses induced by the welding process and distortions in the welded structure.

Thermo-mechanical analysis shows that the tensile residual stress nearly equivalent to the yield stress of the plate material is present along and across the welding centerline. Finally, the plate suffers from compressive stresses approximate to the yield strength value along the welding centerline. In contrast, nominal tensile transverse residual stress is observed across the welding centerline at the end of the thermal cycle. Longitudinal and transverse shrinkages are observed due to the tensile and compressive stresses present in overall plate geometry. The results from the shrinkage strain method showed residual stress values closer to the results obtained from the thermo-mechanical study. Therefore, it can be concluded that the yield level residual stresses are induced in the thermal cycle associated with welding.

Both the shrinkage strain method and thermo-mechanical study suggest that the longitudinal shrinkage is present at the top of the plate. The transverse shrinkage value mapped in the contour plot, however, differs in two methods. The thermo-mechanical study showed lateral expansion, and the shrinkage strain method showed transverse shrinkage.

VII. FURTHER PROSPECTS

- It is suggested to consider rate-dependent plastic properties such as yield strength, poison’s ratio, thermal conductivity, specific heat capacity, and thermal expansion coefficient in the further study.
- The solid-state phase transformation effect can be considered to extend the research. A thermo-mechanical-metallurgical model can provide the details of effect of microstructural changes in residual stresses and distortions caused by the thermal process.

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