Experimental and Numerical Study of Submerged Arc Welding Induced Thermal History, Residual Stresses, Distortion and Weldment Characterization

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1 Introduction

Welding is the most widely used joining process in the fabrication of structures, which includes the conventional industrial applications to modern engineering applications like the fabrication of aerospace structures, nuclear application, high-pressure vessels, marine structures etc. [1]. Welding is known as one of the most complex manufacturing processes, as a large number of variables and factors controls the welding process towards the determination characteristics of the final weld joint [2]. Even though welding is recognized as one of the most significant fabrication processes used in engineering industries, there is limited scientific understanding present in productivity measurement and evaluation of welding processes [2]. During joining of components of a structure, highly localized thermal gradient induces thermal strains in the weld joint and base metal regions resulting in generation of high magnitude of within and around the weld region. Which in turn combine and react to produce internal forces and results in bending, buckling, and rotation. These displacements are termed as welding distortions [1, 4]. Both weld residual stress and distortion can significantly impair the performance and reliability of the welded structures [5]. Therefore, they must be critically dealt with design and manufacturing phases to ensure intended in-service use of the welded structures. Over several fusion welding processes, one of the established techniques for welding big structure is submerged arc welding (SAW) process. The quantitative assessment of distortion and residual stress of an integrated structure is of paramount interest to the researchers [6-11].

The present study is focused on the 3D-FE thermo-mechanical analysis of submerged arc welded mild steel joints to predict the thermal profile, residual stress and angular deformation in the welded structure and develop mitigation technique to minimize the effect of residual stress and distortions. During modeling, the effect of temperature dependent material properties and material deposition were taken care of. sequential thermo-mechanical elasto-plastic Finite Element (FE) analysis was performed to predict the thermal history, residual stresses and distortion. An equivalent loading technique was applied to predict the angular deformation in large structure. An avocado configuration new heat source model was developed to predict the thermal profiles. Experiments were performed to validate the predicted results. Effect of process parameters, joint geometry and effect of surface active elements on the weld bead geometry and mechanical properties were also studied. Optimal process parameters were found out to achieve desired mechanical properties of the welded joints.

2 Research objectives

Based on research gaps found in the published literatures the following objectives were formulated.

- Prediction of thermal history and residual deformation of single pass single sided butt joints and single & double sided fillet joints.
- Development of FE transient elasto-plastic thermo-mechanical model to compute the influence of tacking sequence on residual stress and distortion
- Development of a FE thermo-mechanical model to study the effect of welding sequence on thermal history, residual stresses and distortion in fillet welds.
- Comparative study of residual stresses and angular deformation between single and double sided fillet welded joints.
- Estimation of weld induced distortion of large structures using an equivalent loading technique.
- Development of a new heat source model i.e. avocado-configuration volumetric heat source model with more accurate consideration of the shape of the moving heat source. Prediction of the

temperature distribution and the weld-pool dimensions using the newly developed avocado-configuration heat source model.

- Study of the effect of activated flux on weld bead geometry and mechanical properties.
- Study of the influence of edge process parameters on weld mechanical properties
- Optimization of the welding process parameters using Taguchi method and Grey relational analysis for getting the best weld mechanical property.

3 Modelling Methodology

3-D transient elasto-plastic thermo-mechanical FE models considering the temperature dependent material properties [42] were developed to simulate the thermal history, residual stress and angular deformation of butt & fillet weld joints using FE package ANSYS 12.0. Density of the material was considered constant. Linear Newtonian convective cooling was assumed in all the surfaces except the weld zone. For finding out the residual stress and angular deformation distribution pattern over the entire welded plate, first transient thermal analysis was carried out to find out the nodal transient temperatures. In the second part, the nonlinear elasto-plastic analysis was done by using the result obtained from the transient thermal analysis with consideration of moving heat source, material deposition, elastic-plastic behavior of the base material and joint geometry. For 3-D FE modelling and analysis eight nodded brick elements were used for the thermal analysis and similar eight nodded elements were used in the structural analysis. Here non uniform meshing was applied to save the computation time. The mesh size gradually increases from the center of the weld line to away from the weld line. A new welding heat source was developed to predict the thermal history of submerged arc welded joints. An equivalent loading technique was applied to reduce the analysis time for the prediction of angular deformation of large structures.

4 Results and discussion

The present investigation was performed based on the chosen research objectives mentioned in section 2. The brief results obtained from the present work have been discussed in the following sub-sections.

4.1 Thermo-mechanical analysis of square butt welded joint

A 3-D FE numerical transient elasto-plastic thermo-mechanical model was developed to predict the thermal history, distortions of single pass single sided square butt joints of 8 mm to 12 mm thick MS plates using submerged arc welding. Figure 1 shows the thermal profile of 8 to 12 mm thick plates along center of the weld line. Figure 2 shows the experimental and numerical welding distortion patterns for 10 mm thick plate (parallel to weld line). It can be seen from the Figure 1 that for same welding parameters the welding temperature increases with decreasing of thicknesses and cooling rate increases with increasing of thicknesses.

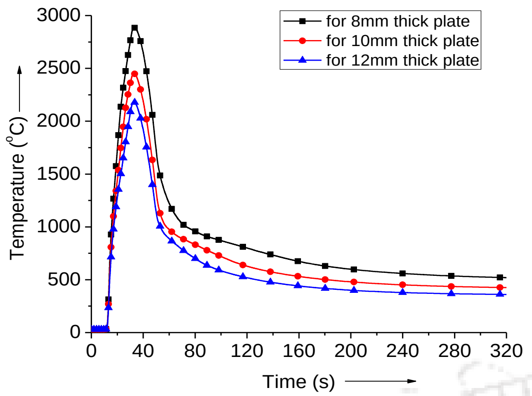

Figure 1 Temperature distribution at top surface of weld

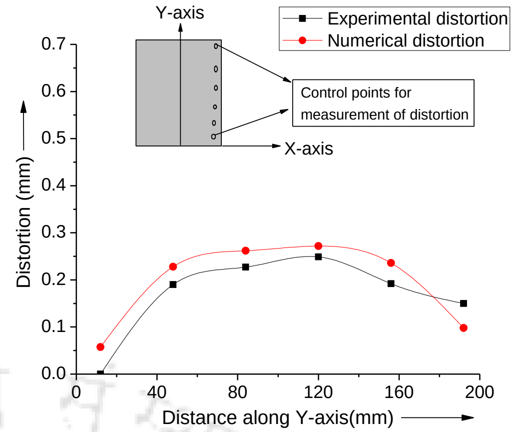

Figure 2 Comparison of numerical and experimental distortion

4.2 Prediction of thermal history and angular deformation of double sided fillet welding

To weld the double sided fillet joint, welding was performed in two successive passes therefore the transient thermal history was analyzed for both the sides. Figure 3 shows the transient thermal history for left side of welded plate where the first pass was performed. Temperature distribution from the center of the weld to away from the weld line was plotted.

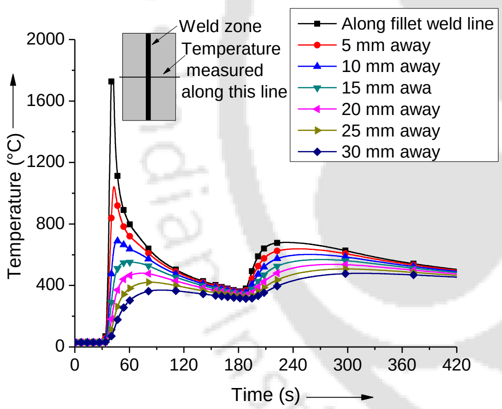

Figure 3 Temperature distribution for the first side of double sided fillet welding

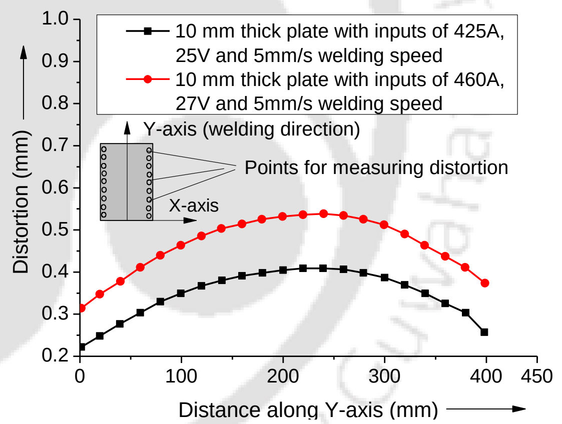

Figure 4 Comparison of angular distortion

Angular deformation was predicted for different welding conditions of double sided fillet welds. In the FE modelling the numerical angular distortions were plotted based on the nodal deflections from the non-linear elasto-plastic thermo-mechanical analysis at the edges of the plate. Figure 4 shows the FE angular distortion for different welding parameters at the edges of the joint models.

4.3 Influence of tacking sequence on residual stress and distortion

Tack welding is a compulsory task in a welding structure. Generally, a number of tack welds are made in a structure before the final welding process. Hence the positioning of tacking as mechanical boundary constraints may influence the residual stresses level and distortion for the whole structure. In this work the effect of tacking sequences on residual stress and distortion were studied for four different tacking sequences. Figure 5 illustrates the distortions of the fillet welded plate due to the different tacking sequences i.e. TS-I to TS-IV. The contour of angular deformations of four different cases is shown in Figure 6.

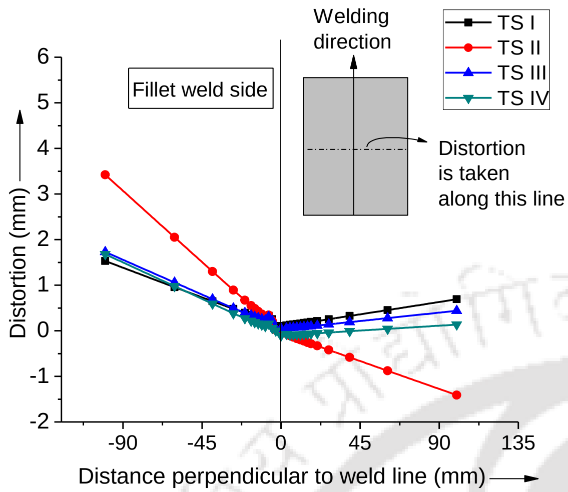

Figure 5 Maximum angular distortions perpendicular to the weld line.

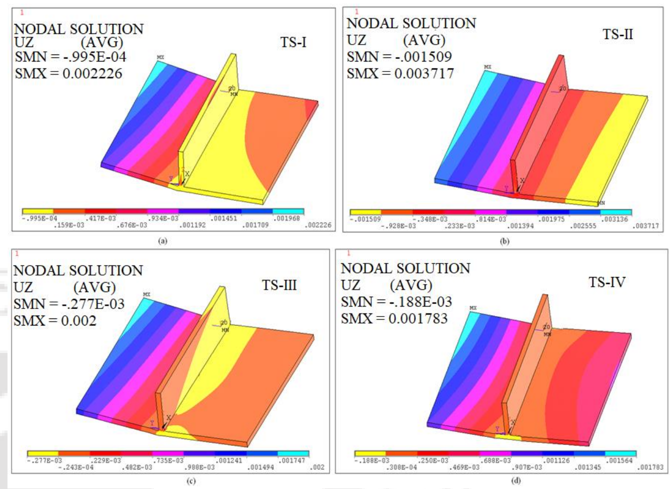

Figure 6 Distortions for four different tacking sequences

It can be seen from Figure 5 that the maximum angular deformation was observed in TS-II (i.e. tack position in 1, 3 and 5). Figure 6 shows that the angular distortion in the fillet side is more and in the opposite side it is less in all four cases, which means the angular deformation is completely unsymmetrical in nature.

4.4 Prediction of welding sequence induced thermal history, residual stresses & distortion

Large stiffened structures are generally joined by several welding passes which generates thermal stresses and angular deformation and finally premature failure of the structure. The different welding sequences lead to non-uniform heating and cooling i.e. creates complex welding residual stress and angular deformation in the structure. Experimental and numerical analysis were carried out on the effect of four different welding sequences on submerged arc welded fillet joint.

From Figure 7, it can be observed that the trends of the predicted thermal history are similar and well matched with the experimental ones. Four different welding passes went through the same sample, therefore the temperature raises & cools for four times which depicts the variation of the thermal gradients involves during the welding of a multi-pass sample. The developed model was used to predict the residual stresses and angular deformation. Figure 8 shows the plot of longitudinal residual stress in the direction perpendicular to the weld line for four different welding sequences. It can be seen from the Figure 8 that residual stresses are tensile in nature near the weld line and compressive away from the weld line. The maximum magnitude of the longitudinal residual stress was found to be more than the transverse one.

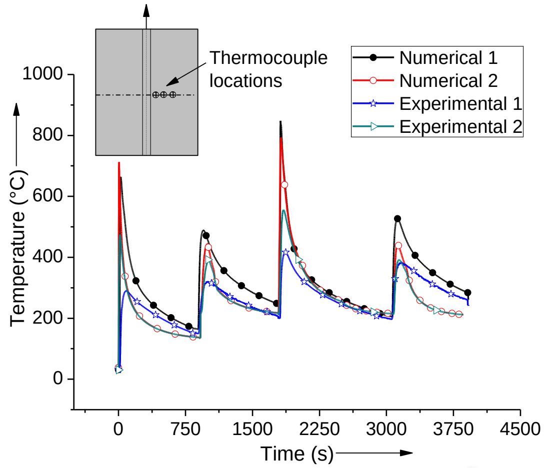

Figure 7 Comparison of predicted and experimental time temperature history for WS-IV

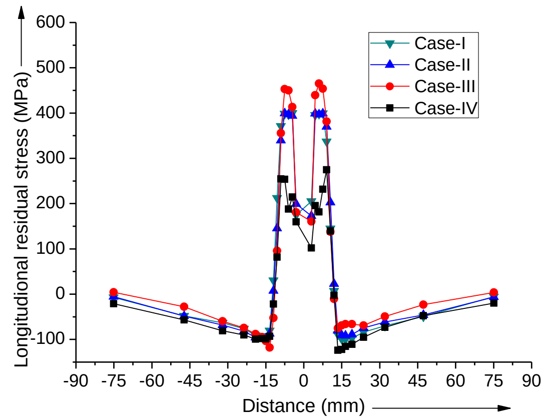

Figure 8 Longitudinal residual stress perpendicular to the welding direction

The comparison between numerical and experimental angular deformation were carried out, which showed a maximum error of 13.14%. Thus, it can be understood that by choosing suitable welding sequence, the angular deformation in a welded structure can be controlled.

4.5 Weld induced distortion of large structure

The conventional coupled transient, nonlinear, elasto-plastic thermo-mechanical analysis involves huge computational time. Computing a weld sample of small size with single pass itself takes several hours, which will be a huge amount of time in case of large structures consisting of several welding passes thus there is a real need of an efficient alternative technique to predict the post weld distortions. In the present work an attempt was made to determine the deformation in a large structure using equivalent load technique which reduces the total analysis time drastically.

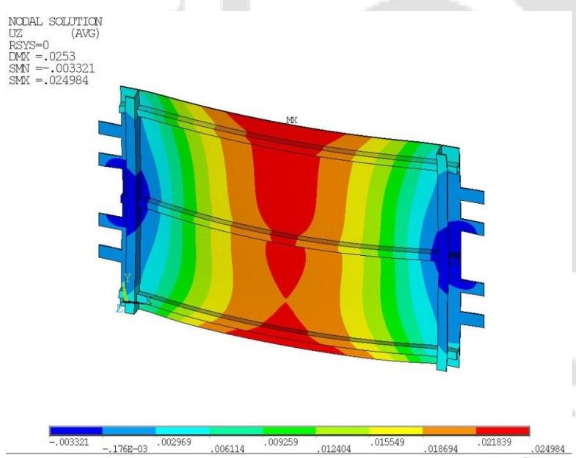

Figure 9 Deformation of a large welded plate

Equivalent load method is based on inherent strains which are a function of the highest temperature and degree of restrain. Equivalent loads are calculated by using the inherent strain components. Figure 9 shows the deformation of a large welded plate (2000 × 1400 × 5 mm) with 3 longitudinal stiffeners (40 × 40 × 6 mm) and 2 transverse stiffeners (75 × 50 × 6 mm). The equivalent loading technique is used to predict the distortion in this large structure. The loads were first applied on the longitudinal stiffeners. After getting the solution of longitudinal stiffeners, the loads were applied on the transverse stiffeners to get the final solution.

The time taken for this equivalent loading technique contains of two parts i.e. (i) time taken for transient thermal analysis of a small welded sample and (ii) time taken for static structural analysis of actual large structure. This first part of time is always almost constant for all type of large structural analysis but the second part of time is depends on size of the structure which is also significantly very small for static structural analysis compare to transient, non-linear elasto-plastic thermo-mechanical analysis. It was seen that the structural analysis time is very less while the equivalent load technique is used hence saves a lot of time as well as resources. So, this technique drastically reduces the time required for transient thermal analysis and nonlinear elasto-plastic thermo-mechanical analysis of actual large structure.

4.6 Development of an avocado shaped new heat source model

An avocado-configuration volumetric heat source model with Gaussian distribution has been developed for modeling of fusion welding processes. The end crater shape of the weld bead of submerged arc welding is similar to the cross section of an avocado. Usual properties of an avocado configuration are symmetry about one axis, smaller at one end, convex nature, and have a positive curvature. The three dimensional avocado-shape in Cartesian coordinate system is defined by modifying the ellipsoidal as follows:

$$\frac{y^2}{b^2} + \left\{ \frac{x^2}{a^2} + \frac{z^2}{c^2} \right\} \times \left\{ t(y) \right\} = 1 \quad (1)$$

Here it is considered that the heat source moves with a local coordinate system (x, y, z) in 'y' direction. Therefore the shape and degree of asymmetry of the avocado-curve is decided by the semi-axes lengths of ellipsoid (a, b, c) and the function *t(y)* provides the necessary non-uniformity in the heat source power density distribution. The functional form, *t(y)* considered in this present work is shown in Equation 2.

$$t(y) = \frac{1}{e^{my}} \quad (2)$$

where 'm' is a constant which magnitude decides the shape of the heat source The shape was assumed from the end crater geometry of a weld bead in submerged arc welding. The semi-major axis length of the forward and rear ellipsoid used in this study are taken from experimental study. Figure 10 shows the comparison of the present development with 2D shape of ellipse, egg shape while considering same semi-axis lengths.

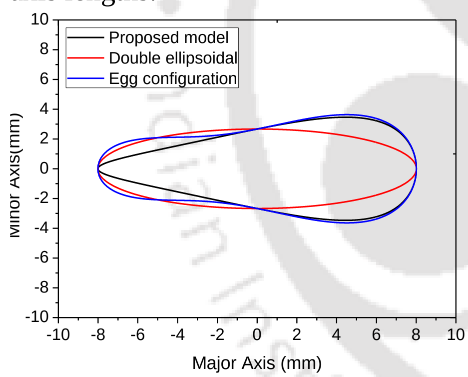

Figure 10 Comparison of 2D shape among existing models and the present model

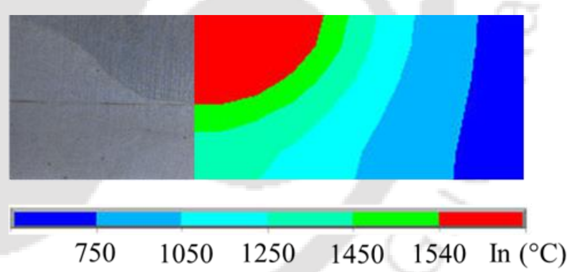

Figure 11 Comparison of experimental weld macrograph with predicted thermal profile with the new model

During welding the heat source moves in welding direction with a constant welding velocity so the heat source power density distribution is non-uniform. Therefore, the heat distribution in front and rear part of the avocado-shape should not be the same. It is also evident from the shape of the proposed avocado configuration that heat deposition in front and rear parts are different. To consider the effect of non-uniformity, the heat density distribution in the front and rear parts of the heat source can be expressed as follows:

$$q_{f(x,y,z)} = q_m \times A_f \times e^{\left\{ -\left[By^2 + \left(Ax^2 + Cz^2 \right) \times \frac{1}{e^{my}} \right] \right\}} \quad (3)$$

$$q_{f(x,y,z)} = \frac{6\sqrt{3}.Q.A_f\ e^{\left\{-\left[\frac{3}{(b-p)^2}y^2+\left(\frac{3}{a^2}x^2+\frac{3}{c^2}z^2\right)\times\frac{1}{e^{my}}\right]\right\}}}{\pi\sqrt{\pi}.a.b.c.\,e^{\frac{m^2b^2}{12}}} \tag{4}$$

where A_f is the fraction that accounts the amount of heat deposition in front portion and A_r accounts the heat deposition in rear part of the arc. Bead on plate experiments were performed, cross section of the welded samples was taken to measure the weld poll dimensions. A comparative study of the predicted weld bead shapes using the proposed avocado configuration model & double ellipsoidal model is shown in the Figure 11. A fair agreement for a wide range of process parameter can be found.

4.7 Effect of welding parameters on weld bead geometry & mechanical properties

The weld characteristics of SAW process are greatly influenced by its control parameters [15]. In the present study, four levels of four process parameters, i.e., current, voltage, welding speed and length of stick out were considered to study the effect of these parameters on weld bead geometry and mechanical properties.

It was observed from experiments that the welding input parameters have considerable effect on weld bead geometry. Figure 12 shows the effect of welding current on weld bead width. As current level increases bead width increases. Increase in current rises the electron density at the welding arc, the total heat content of the droplets increases i.e. more heat being transferred to the weld pool which results in deeper melting & penetration.

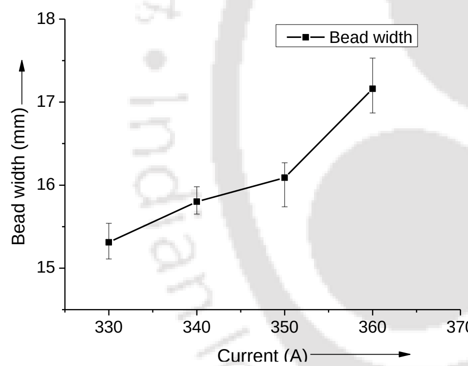

Figure 12 Effect of current on bead width

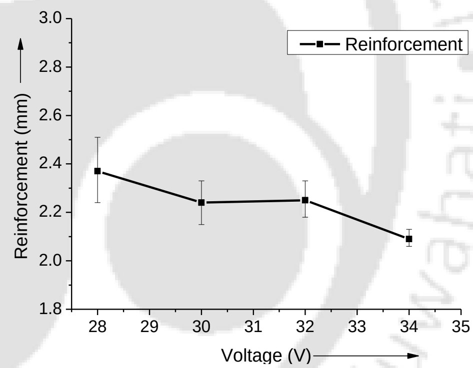

Figure 13 Effect of voltage on weld reinforcement

Welding reinforcement (Figure 13) is influenced by arc voltage. It can be seen that with the increase in voltage reinforcement decreases. With the increase in voltage, flatten upper surface can be seen which reduces the weld reinforcement. Hardness test was carried out at different weld zones of all samples. Hardness ranges were observed from 156-160 HV at base metal, 154-170 HV at HAZ region and 162-190 HV at weld region. Hardness values in both HAZ and weld metal were found to be higher than base metal in all the samples due to the grain refinement above recrystallization temperature. It was found that current effects on overall weld bead geometry i.e. with increase of current the weld bead width, bead height and penetration increases. However, with the increase of voltage the weld bead becomes wider and flatter but weld penetration remains almost constant. With the increase in welding speed, the overall size of weld geometry decreases but with the increase in length of stick-out, overall size of weld geometry increases.

4.8 Effect of surface active elements on weld bead geometry

Addition of surface active elements can alter the weld bed geometry, for that reason effect of different types of surface active elements on weld bead geometry was studied. In this present work four different types of elements containing SiO_2, Cr_2O_3, TiO_2, and mixture of all fluxes were used. A comparative study on weld pool geometry, weld penetration, bead width and reinforcement was performed between welding with and without surface active elements.

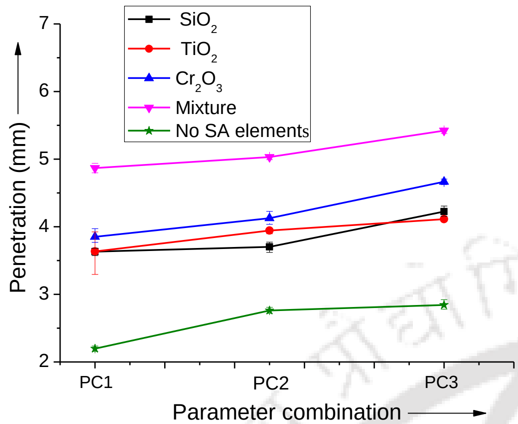

Figure 14 Effect of surface-active elements on weld penetration

After the welding, the three output parameters viz. weld bead geometry, penetration and reinforcement were measured. Among the all cases, the mixture of three surface active elements produced most noticeable effect on weld penetration (Figure 14). It increased the penetration more than twice as compared with conventional submerged arc welding i.e. without surface active elements. SiO_2 activated flux shown least amount of penetration. The activating elements increases the surface tension of molten metal which leads to increase the striking and gets more penetration as compare to the welding without activating flux.

4.8 Effect of included angle on mechanical properties

For welding thick joints, edge preparation is necessary. Edge preparation takes lots of extra time & effort. Amount of weld metal deposit influences the mechanical property of the joint. Thus weld joint design has significant effect on weld economy as well as the mechanical properties of the welded structure. Experiments were conducted on 10 mm thick plate to study the effect of included angle on mechanical properties of single V-butt joints. Included angle were varied for same root opening in single V-groove butt joints while all the other welding parameters were kept constant.

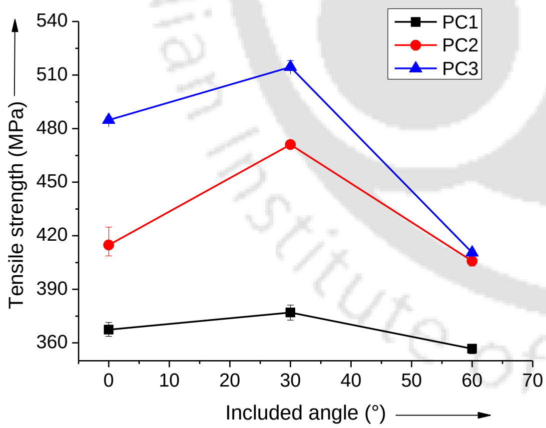

Figure 15 Effect of included angle on tensile strength

Figure 15 shows the variation of tensile strength for all the joint geometries at three parameter combinations (PC1-3), small included angle (30°) of single-V shows the maximum ultimate tensile strength followed by flat butt joint and large included angle of single-V joint respectively. Smaller included angle shows more tensile strength because groove edge accommodates more metal deposition than square butt edge and therefore the bonding strength is higher than that of straight square butt edge. More the amount of weld deposit, higher the expansion and contractions consequently residual stresses increases in the weldment and the heat affected zone. Tensile strength is higher in V-grooved edge over flat edged joints because the bonding strength is more here.

4.9 Effect of process parameters on microstructure and mechanical properties

Total sixteen numbers of experiments were conducted with different process parameters which were designed based on Taguchi design of experiment method. Four different important process parameters of submerged arc welding (SAW) i.e. the welding speed, current, voltage and length of stick out were varied over four different levels. The maximum magnitude of hardness was seen in the fusion zone because of the presence of the higher carbon percentage due to the filler wire. The hardness of the heat affected zone was observed lower than the fusion zone but more than the base metal due to grain refinement. Figure 16 explains the variations of hardness value with distance.

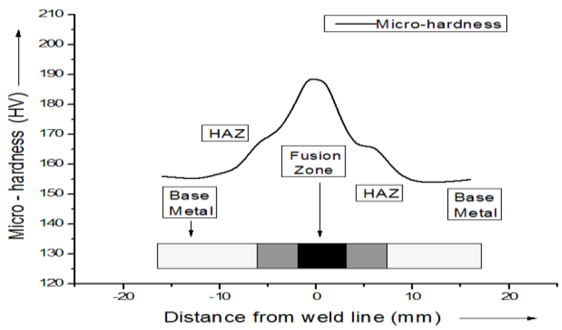

Figure 16 Micro-hardness variation with distance

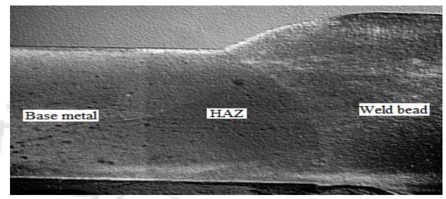

Figure 17 Different weld zones (macrograph)

To study the combined effect of welding parameters rate of heat input was considered. It was observed that with increase in rate of heat input the tensile strength and hardness increases. It was also observed that for getting full penetration in the single sided single pass butt welding of 8 mm mild steel plates without edge preparation the rate of heat input can be kept in the range of 1.71-2.35 kJ/mm. The Figure 17 shows the three different microstructure zones of the welded sample. Fine grain structure was found in the HAZ due to grain refinement and grain coarsening can be seen in the weld zone due to reaching the melting point. Combination of both fine and coarse grain were observed in the intermediate zone between fusion and HAZ.

4.10 Prediction of optimal process parameters

Submerged arc welding process consists of multi-input parameters, therefore it is essential to determine the optimal process parameters for achieving desired quality characteristics of the weldment. Fist single response optimization was carried out for getting the optimum process parameters to get maximum yield strength of the welded joints. To predict the optimal process parameters for individual responses, Taguchi optimization was performed for the individual responses accordingly. To predict optimal process parameters for all the responses together multi-objective optimization process is essential. So, multi-response optimization of the all the responses together was carried out using utility theory along with Taguchi method. Predicted results were verified by using confirmation test.

5 Conclusions

From the preceding investigations, the following conclusions have been made:

- 3D FE nonlinear elasto-plastic transient thermo-mechanical model was successfully developed for both butt and fillet welding joints which were validated with experimental results and published literature. A good agreement between the predicted and experimental results was observed with an error of 5 to 10%.
- From the comparative study of residual stresses and angular deformations between single and double-sided fillet welded mild steel joints it was observed that single sided fillet welding shows non-uniform pattern of the residual stress distribution in the left and right side of the stiffener whereas it is almost uniform for double sided fillet welding. The peak magnitude of residual stress is more in case of single side fillet welding compare to that of double sided fillet welding. However, higher magnitude of angular deformation is observed in case of double sided fillet welding.
- The tacking positions also have a significant effect in residual stresses and angular distortion distribution. It was observed that the tacking positions opposite to fillet weld side have negligible

effect on residual stress distribution whereas the tacking positions in fillet weld side have significant effect on uneven distribution and increment of residual stresses. So, the number of tack welds should be as minimum as possible if not avoidable and it should be placed opposite to the fillet weld side.

- It was observed that welding sequences have prominent effects on both distortion & residual stresses. The angular deformation can be reduced significantly by choosing proper welding sequences.
- Prediction of distortion of large welded structure with multiple welding passes is a very difficult task due to limitation of computation resource. An equivalent loading technique with the bar-spring analogy was successfully implemented to predict the weld induced distortion of large welded structure. The elastic FE analysis using equivalent loading technique involves very less computational time as compared to the 3-D FE nonlinear elasto-plastic thermo-mechanical analysis.
- Based on experimental study, an avocado shaped volumetric heat source was developed. The generalised form of the avocado-configuration heat source consists of limited number of model parameters, which can provide a real non-uniform shape of moving heat source of fusion welding. The developed heat source model was validated with experimental results. A good agreement between the predicted and experimental results was observed with an error of 8 to 10%.
- Single pass single sided experimental square butt joints were successfully made on 8 mm to 12 mm thick plates. Through thickness fusion along with adequate top and bottom reinforcements were achieved using flux-filled reusable backing bar.
- From mechanical characterization, it was observed that the maximum hardness was observed in the weld zone and which decreases gradually away from the weld line towards base material. The increment of hardness in the weld zone was more for lower welding speed, higher voltage and higher current. Maximum hardness at weld zone and HAZ were around 20 % and 12% more than the base material respectively.
- Hardness shows an increasing trend with increasing of current and voltage. Hardness shows less variation with speed. Length of stick out has minor effect on bead as well as micro-hardness.
- None of the tensile samples failed in the weld zone, failure was seen in between the base metal and heat affected zone. Based on UTS the maximum joint efficiency was 96%.
- It was seen that with the increase in weld voltage, the bead width becomes flatter but top reinforcement decreases. However, with the increase in current both top reinforcement and bead width increases. Welding speed has negative effect on weld bead dimensions; the overall bead geometry reduces with the reduction in welding speed.
- Surface active elements play a significant role for welding of thicker plates. It was found that by choosing appropriate activated flux weld bead penetration can be increased by more than two times i.e. 221%.
- It was seen from the results of three different joint geometries that V-butt joint geometry with 30° included angle produces superior mechanical property than the other joint geometries. Maximum ultimate strength and hardness were obtained at 30° included angle which were 99 % and 129 % to that of the base material respectively.
- To get optimal process parameters for desired weld quality, Taguchi optimization technique was used for single output problem. To determine the optimal process parameters for multiple output problem, Grey relational analysis in combination with Taguchi method was used. From ANOVA it was observed that welding voltage was having highest contribution, followed by welding current & welding speed and length of stick had the least contribution on the weld quality characteristics.

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