Numerical Simulation of Arc Welding Investigation of various Process and Heat Source Parameters

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ABSTRACT The present study describes a combination of numerical simulation and experimental validation to study the temperature distribution and prediction of fusion zone (fz) and heat affected zone (haz) in gas tungsten arc welding of low carbon steel. Welding experiments are carried out on weld coupons of 3 mm thick sheet metals of 150 x 50 mm with a 2 mm square gap between them. Simulation of the entire process is accomplished by using authors written subroutines in ansys® 10.0, general purpose finite element software. The primary objective of the present study was to develop computationally efficient numerical simulation technique with in the commercially available finite element software(s) domain, for the accurate prediction of the temperature history, size of fusion and heat affected zones of the weldments. Additionally the effects of varying various significant welding and geometric parameters on the response of the weldments are also investigated with the anticipation to further utilization in the prediction of the welding induced imperfections like weldment distortions, residual stresses formation and the complex phenomenon of weld solidification cracking. The induction of carefully measured experimental data into the numerical simulations, showing close co-relation between the simulated and experimental investigations in the present study presents the significance of the numerical techniques developed for the precise prediction of transient thermal response of the weldments for the large scale industrial usage in nuclear, aeronautical, aerospace and marine engineering domains.

INTRODUCTION

The critical first step in predicting the weld induced imperfections like residual stresses, deformations, and weld solidifications cracking etc. is to accurately compute the transient temperature fields during the arc welding process. This is necessary because the temperature has a first order effect on the microstructure, strain, stress and ultimately on the formation of defects in welds while they have at most a second order effect on the temperature fields [1]. The problem of distortion, residual stresses, and reduced strength of a structure in and around a welded joint are a major concern of the welding industry for decades. These problems primarily result directly from the thermal cycle caused by localized intense heat input in arc welding process [2]. Hence for the development of effective simulation strategy for weld analysis, the accurate prediction of thermal history is of key importance. Additionally the effects of various welding process and heat source parameters on the transient temperature states must be accurately known. The first major contribution in the field of weld thermal analysis is the analytical solution for a welding
heat flow problem by Rosenthal which has been used worldwide to predict welding thermal history and cooling rates. The exact theory of heat flow due to a moving point source was first applied to arc welding by the author in 1935 using the experimentally established principle of a “quasi-stationary” state, that is, an observer stationed at the point source fails to notice any change in the temperature around him as the source moves on [3]. Later it was shown that Rosenthal’s analysis which assumes a point, line, or plane source of heat is subject to serious error for temperatures in or near the fusion and heat-affected zones. The infinite temperature at the heat source assumed in this model and the temperature sensitivity of the material thermal properties (a temperature independent mean value is assumed) increases the error as the heat source is approached. Pavelic et al. first suggested that the heat source should be distributed [4]. He proposed a Gaussian distribution of flux deposited on the surface of the work-piece. Later, some authors have suggested that the heat source should be distributed throughout the molten zone to reflect more accurately the digging action of the arc [1]. A double ellipsoid configuration of heat source was proposed by J. Goldak [1] so that the size and shape of the heat source can be easily changed to model both the shallow penetration arc welding processes and the deeper penetration in laser and electron beam processes. In addition, it has the versatility and flexibility to handle non-axis-symmetric cases such as strip electrodes or dissimilar metal joining.

Welding stresses arising from the temperatures gradients due to the moving heat sources and deformations have close analytical relations. Due to heating and cooling, thermal stresses occur in the weld and the adjacent areas. The strains produced during the heating phase always induce plastic deformation of the metal. The stresses resulting from these strains combine and react to produce internal forces that cause a variety of welding distortions. Welding-induced residual stresses and shape-change behavior can play a very important role in the reliable design of the welded joints and welded structures. Finite element techniques have been used in the prediction of welding residual stress and distortion for more than two decades [5]. Due to the nature of the process, additional complexities are involved in the FEA of welding compared to traditional mechanics, such as temperature and history-dependent material properties, high gradients of temperature, stress and strain fields with the respect to time, large deformations in thin structures, phase transformation and creep phenomena [6]. The problem of distortion, residual stresses and reduced strength of structure in and around welded joints are a major concern of welding industry, primarily in aerospace industry where safety and economy are important issues.

PRESENT STUDY

The present research work presents a transient non-linear thermal simulation of plate butt joint by arc welding processes using FE heat transfer analysis. A heat source model is presented based on the Goldak’s method and MATLAB® scripts are developed in order to calculate the heat flux distributions and define a moving heat source into simulations by using FE software ANSYS® [7]. Full three-dimensional FE models are developed in ANSYS® for the simulation of complex, highly nonlinear phenomenon during the arc welding process with filler metal deposition, as it was used by many researchers [8, 9, 10] in the past to tackle the nonlinear problems with acceptable accuracy levels. The results from the developed modeling approach were verified by welding experiments on the same geometry with similar parameters in order to establish quantitative correlations between FE simulations and experiments. The transient temperature
distribution and variation of the welded plates during welding process were predicted. The fusion zone and heat affected zone were also obtained. The effect of the heat source distribution, energy input and welding speed on temperature was investigated. The results showed that temperature distribution and variation in the welded plates are sensitive to the heat source distribution and welding process parameters. The work presented here would provide a basis for further investigations of welding distortions, residual stresses and weld solidification cracking phenomenon.

**Finite Element Simulation Strategy**

A three-dimensional finite element analysis strategy is developed to benchmark the experimental results from section 3.0. The size of the specimen plate is 150mm x 100mm x 3mm (length x width x thickness). Because of symmetry, only one half of the plate is modeled. The heat transfer analysis to simulate the GTA welding process is conducted through the author written subroutines in ANSYS®. Taking into account the weak nature of mechanical to thermal fields coupling, the first part of the sequentially coupled elastic-plastic thermo-mechanical analysis is discussed here in the present study and the effects of various heat source and welding process parameters on transient temperature distributions, boundary and shape of FZ and HAZ are presented in detail. The combined heat transfer coefficient for convection and radiation [11] is calculated and applied on all the surfaces (except the symmetry plane) as thermal boundary condition. The heat loss from the surfaces are modeled from the equations-1 and 2.

\[ q_{\text{loss}} = q_{\text{convection}} + q_{\text{radiation}} \]  
\[ q_{\text{loss}} = h_{\text{total}} \times A(T - T_{\text{amb}}) \]

where, \( A \) is the surface area, \( T \) is current temperature, \( T_{\text{amb}} \) is the ambient temperature and \( h_{\text{total}} \) is combined convection and radiation coefficient, given by the following equation.

\[ h_{\text{total}} = [h + \varepsilon \sigma (T + T_{\text{amb}})(T^2 + T_{\text{amb}}^2)] \]

where,
- \( h \) = Thermal convection coefficient  
  (8 W/m²·°K in the present study)
- \( \varepsilon \) = Radiation emissivity
- \( \sigma \) = Stefan Boltzmann constant  
  (5.67 x 10⁻⁸ W/m²·°K⁴)

On the surface of the steel under investigation in the present study, \( \varepsilon = 0.51 \) is used which is the average value for hot rolled steel plates. \( T_{\text{amb}} \) is taken as 300°K equal to the preheat temperature. The heating time along the weld path is about 52 sec with a torch speed of 3.0 mm/s, and the complete welding sequence is divided into 78 incremental equally spaced load / solution steps of 0.667 s. Stepped load option available in ANSYS® is used for effective application of thermal load during the load step. After extinguishing the arc additional 40 load steps of different lengths
are used for cooling of the weldment. The total cooling time to return to the ambient temperature of 300°C (573.15°K) is about 23 minutes from the start of the cooling phase.

**Finite Element Model in the Present Study**

One-half symmetric 3D FE model for the welding of coplanar plates with v-groove developed in ANSYS® is shown in Fig. 1. The element type in thermal analysis is SOLID70 (linear 8 node brick element with one degree of freedom, i.e., temperature at each node). Further details about the selected elements may be found in [7]. The finite element statistics for the model is:-

Total No. of nodes : 1246  
Total No. of elements : 9000

High temperature and flux gradients are anticipated in and around the FZ and HAZ therefore a relatively fine mesh is used within a distance of 10 mm from weld line (Wₐ). Away from the HAZ the element size increases with an increase in the distance from Wₐ. In weld direction, the element size is kept constant equal to 2 mm. Within the anticipated HAZ dimension of 10 mm on each side of the Wₐ in transverse direction, the element size of 1 mm is used. The element size away from weld region increases with the increase in distance. In thickness direction there are total three elements, 1 mm each to facilitate for v-groove modeling. Two tack welds on the start and end of the weld are modeled, each of which comprises of 2 elements (4 mm) in weld direction and 2 elements (2 mm) in transverse directions and 3 elements (3 mm) in thickness direction. Tack lengths positions in the FE model are in accordance with the physical weld sample.

**Fig. 1: 3D FE model used in the present study**
Moving Heat Source Model

The welding induced imperfections like residual stresses and deformations are believed to be due to highly non-uniform temperature fields generated during welding. Both the residual stresses and deformations, are highly sensitive to transient temperature distributions, which itself is a function of total heat applied and heat distribution patterns within the domain. Thus for the determination of realistic temperature profile in the target application, a very careful and accurate modeling of heat source is required. During the last four decades several developments in the heat source modeling have been reported in the literature, a very brief introduction of which can be found in [B1].

In the present study, the welded plates and filler material is modeled as solid body. The most widely acceptable double ellipsoidal heat source model, presented by Goldak et al [1] is used to present the heat generated by the welding torch. The model gives the Gaussian distribution and has excellent features of power and density distribution control in the weld pool and HAZ. The heat source distribution as shown in Fig. 2 combines two different ellipses i.e. one in the front quadrant of the heat source and the other in the rear quadrant [13].

![Heat Source model used in the present study](image)

The spatial heat distribution in a moving frame of reference can be calculated with the governing equations (3) and (4) [1]

\[
q_f = \frac{6\sqrt{3}\eta Q f_f}{\pi \sqrt{\pi a_f bc}} e^{-3\left(\frac{x^2}{a_f^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2}\right)}
\]

(3)

\[
q_r = \frac{6\sqrt{3}\eta Q f_r}{\pi \sqrt{\pi a_r bc}} e^{-3\left(\frac{x^2}{a_r^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2}\right)}
\]

(4)
where,
\[ Q = VI \quad \text{and} \quad f_f + f_r = 2 \]

- \( Q \) = Total heat input (watts)
- \( V \) = Welding voltage (volts)
- \( I \) = Welding current (amperes)

**Heat Flux Distribution for FE Model**

In order to simulate the welding torch movement with the specific welding speed, the calculated volumetric heat flux densities have to be assigned to specific elements around the welding areas in the FE model. In this case, the origin of the coordinate system is located at the centre of the moving arc. A user subroutine written in APDL is used to calculate the centroidal distance of elements from the moving arc centre corresponding to the arc position at any instant. Based on the FE mesh generated by the ANSYS®, definitions of the welding process parameters and characteristics of the heat source transient heat fluxes representing the moving the distributed heat source can be calculated on specific positions in welding areas. The heat source is assumed to move through volume and calculated heat is applied to elements as volumetric heat generation. The supplementary advantage of volumetric heat generation is that the elements lying on the surface can be used for modeling of surface heat convection which otherwise require additional two dimensional surface elements to suit the purpose. The numerical values of different heat source parameters and welding process parameters used in the study are shown in Table 1 and Table 2 respectively.

Fig. 3 and Fig. 4 represent two corresponding heat flux distributions with different welding process and heat source parameters. The variation of the parameters changes the heat source distributions and magnitude, therefore influences the input of heat flux applied in the weld regions. Consequently it affects the transient temperature distributions in the fusion zone, heat affected zone and peak temperatures in the welded plates [13]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HSP-1</th>
<th>HSP-2</th>
<th>HSP-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_1 )</td>
<td>8 mm</td>
<td>8 mm</td>
<td>4 mm</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>20 mm</td>
<td>12 mm</td>
<td>12 mm</td>
</tr>
<tr>
<td>B</td>
<td>10 mm</td>
<td>8 mm</td>
<td>8 mm</td>
</tr>
<tr>
<td>C</td>
<td>2.5 mm</td>
<td>3 mm</td>
<td>3 mm</td>
</tr>
<tr>
<td>( f_f )</td>
<td>0.6</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>( f_r )</td>
<td>1.4</td>
<td>1.45</td>
<td>1.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>WPP-1</th>
<th>WPP-2</th>
<th>WPP-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V ) (volts)</td>
<td>175</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>( I ) (amperes)</td>
<td>12.5</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>( \eta ) (%)</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>
Modeling of Filler Metal Deposition

Conventional quite element technique [14], which is relatively straight forward and easy to implement by utilizing the ANSYS® embed features of element birth and death, is used in the present work. The whole FE model is generated in the start however; all elements representing filler metal are deactivated by assigning them very low conductivity. During the thermal analysis all the nodes of deactivated elements (except those shared with the base metal) are also fixed at ambient temperature till the birth of the respective element. Deactivated elements are re-activated sequentially when they come under the influence of the heat source (welding torch).

![Power Density](image1)

**Fig. 3:** Power density on upper surface of the plate with heat source parameters HSP-1 and welding process parameters WPP-1

![Power Density](image2)

**Fig. 4:** Power density on upper surface of the plate with heat source parameters HSP-2 and welding process parameters WPP-2

Material Model

In simulation work the same material is assumed for sheet metal and filler metal. Temperature dependent material properties are taken from Karlsson and Josefson [15] as shown in Fig. 5 and Fig. 6. The melting and phase transformation temperatures of the material are taken as 1738\(^\circ\)K and 900\(^\circ\)K respectively. These material properties were presented for carbon-manganese steel with the composition of 0.18\% C, 1.3\% Mn, 0.3\% Si, 0.3\% Cr, 0.4\% Cu.

![Temperature Dependent Thermal Conductivity](image3)

**Fig. 5:** Temperature dependent thermal conductivity of material

![Temperature Dependent Specific Heat](image4)

**Fig. 6:** Temperature dependent specific heat of material
RELIABILITY VERIFICATION FOR THE DEVELOPED FE MODEL

To ensure the reliability of the finite element model developed, TIG welding experiments on two coplanar plates with similar geometric dimensions, weld parameters, and heat source parameters from the base finite element model are conducted. Commercially available mild steel with slight variations in chemical composition from the material model used in the simulation is utilized. Similar approximations were made in the past by many researchers [16, 17] with reasonable comparative results in the measured and predicted results.

Sample from the welded specimen is ground, etched, polished and the macrograph of the cross section is shown in Fig. 7 along with the superimposed cross section at similar time step from the weld experiments. The quantitative comparison of measured and predicted FZ and HAZ values are shown in Fig. 8. From Fig. 7 and Fig. 8, it is evident that predicted results agreed well with the experimentally measured FZ and HAZ. Thus, the developed models have been experimentally validated.

SCOPE OF THE PRESENT RESEARCH

The primary objective of the present research is to address the evolution of thermal effects, fusion and heat affected zones of welded thin sheet metals of commercial mild steel by finite element methods. A comprehensive analysis for the Gas Tungsten Arc Welding (GTAW) commonly known as Tungsten Inert Gas (TIG) welding process for two coplanar plates with symmetry option is presented. The Scope of the present study is limited as follows:

1. Study the effects of double ellipsoidal heat source model by varying the heat source parameters. Three different set of heat source parameters are used and their effects on the evolution of temperature gradients, fusion and heat affected zones during the arc welding phenomenon are investigated. Different set of GOLDAK’s double ellipsoidal heat source parameters used are shown in table-1. The correspoding distribution in power densities are shown in Fig. 3 and Fig. 4.
2. Study the effects of welding process parameters on the temperature profile, fusion and heat affected zones. Three different heat inputs are used by varying the welding process parameters. The base heat input value from the experiments, govern by the arc voltage and current values of 12.5 volts and 175 amperes respectively with arc efficiency of 90%. To study the effects of variation in heat input, two additional studies with values of welding process parameters as shown in Table-2 are also used.

3. Study the effects of varying welding speed on the temperature profile, fusion and heat affected zones. Three different torch speeds are used for comparison purpose. The base value govern from the welding experiments is taken as 3 mm/sec. For comparison purpose two additional studies with torch speeds 6 mm/sec and 9 mm/sec are also conducted.

RESULTS AND DISCUSSION

Fig. 9 shows the temperature distribution of the welded plate after 32.667 seconds and the heat source is at a distance of 98 mm from the weld start position. It is evident from the figure that the temperature around the torch reaches 2110°K suggesting melted material in the fusion zone (FZ). Next to fusion zone, the presence of higher temperatures indicates the presence of heat affect zone. A small area ahead of the heat source also shows comparatively higher temperature because of the front parameter of heat source model. The heat input from the heat source to the weldments gradually transferred to the rest of the base plate in all directions due to conduction, convection and radiation phenomenon. Also the cooling effects can be visualized by the decreasing temperature of the weld start position where the temperature drops around 1070°K.

The evolution of temperature gradients, FZ and HAZ due to moving heat source along the weld path is obvious from Fig.9. The maximum temperature attained at the torch location along with the double ellipsoidal heat source distribution is evident. As the heat source moves away from certain point the temperature drops significantly with the passage of time. After 32.667 seconds the melted region (1738°K) of the plate reaches a temperature of 1070°K. It is believed that this high temperature heating with subsequent cooling of the weldments is the only source for the weld induced imperfections. The computed temperature histories of some selected test points throughout the welding heating and cooling sequence are shown in Fig. 10.

The temperature distribution on the top surface (exposed directly to welding torch) of the plate transverse to welding direction with base welding process parameters (WPP-1), heat source parameter (HSP-1) and welding speed of 3 mm/sec is shown in Fig. 11.

In a similar fashion the temperature history along the weld line at different time steps with the same welding process parameters, heat source parameters and welding speed are shown in Fig. 12. Fig. 13 clarifies the temperature distribution in a reference plane taken from the simulation, when the welding torch approaches and crosses the plane. The rapid distribution of temperature in and around the fusion zone and then to the HAZ are obvious. This also shows that heat
Conduction is primarily responsible for most of the heat flow, whereas surface convection and radiation have little effects on FZ and HAZ boundaries.

**Fig. 9: Temperature distribution from FEM**

**Fig. 10: Temperature history of selected test points throughout the welding heating and cooling process**
The effects of varying heat source parameters and welding process parameters on transient temperature distribution and evolution of FZ and HAZ are shown in Fig. 14 to Fig. 17 respectively. Heat source parameters distribution directly affects the boundaries and shape of the FZ and HAZ as shown in Fig. 14. The decrease of the FZ with increase in heat source parameters depicts the lower value of heat density applied to the surface exposed to the welding torch. The heat source parameters also affect the peak temperature considerably in FZ and HAZ as shown in Fig. 15.

The values of HSP-1 as compared to HSP-2 and HSP-3 show considerable peak temperature variations in FZ and HAZ due to significant variations in the parameters. This dictates that the transient temperature distribution is strongly sensitive to the heat source parameters.

**Fig. 11:** Temperature distribution on top surface of plate transverse to welding direction with welding process parameters (WPP-1), heat source parameters (HSP-1) and welding speed 3 mm/sec

**Fig. 12:** Temperature history along the weld line, in weld direction at selected time steps

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As was anticipated, the variation in total heat energy input to the metal i.e. variation of welding process parameters primarily welding voltage, current and arc efficiency significantly affects both the boundaries (magnitude) and shape (heat distribution) of FZ and HAZ along with affecting the peak temperatures in both the zones.

\[t = 0.666\]  
\[t = 1.333\]  
\[t = 2.00\text{ sec}\]  
\[t = 2.666\]  
\[t = 3.333\]  
\[t = 4.00\text{ sec}\]

**Fig. 14: Effects of varying heat source parameters on shape and boundaries of FZ and HAZ**

As seen for heat source parameters, the effects of process parameters also have a little influence on temperature distributions on the rest of the base metal. The comparison of temperature distributions on top surface of the plate transverse to welding direction with varying welding process parameters and welding speed of 3 mm/sec is shown in Fig. 1.
With HSP-1 a gross power of 2187.5 watts is input to the upper surface of the plate. Similarly for HSP-2 and HSP-3 the heat input is 3000 watts and 6000 watts respectively. The gross heat input is used for comparison purpose only as in all the three cases the welding speed and arc efficiency are identical. Further similar heat source parameters are used to explicitly get the effects of the variable heat input. The high input in case of HSP-3 shows significantly higher peak temperature (2563°K) as compared to HSP-2 (1830°K) and HSP-1 (1720°K). An important investigation here is that the peak temperature directly depends upon the total heat input to the plate from the welding torch.

**Fig. 15: Effects of heat source parameters on peak temperatures in FZ and HAZ**

Fig. 16 shows the peak temperature achieved transverse to weld direction (section at z=90 mm) when the heat source is applied at different welding speed to the plates. It is obvious that the increase in speed will result in a shorter stay of the heat source on a specific area, dictating the lower temperatures. The same is indicated from the simulations in Fig. 16. The increase in speed only influences the peak temperatures in FZ and HAZ and has very little effects on temperature in the areas away from the heat source. Fig. 17 shows the predicted temperature profiles along the welding direction with varying welding speed. The maximum temperature from the weld start position (X=0 from Fig. 17) decreases along the weld direction for a specific time step. It is clear that welding speed significantly affects the peak temperature within the FZ and HAZ with no significant effects away from the weld line.

**CONCLUSIONS**

A Gaussian distributed moving heat source model based on Goldak’s heat source model through author written APDL subroutines and MATLAB scripts is implemented and experimentally validated for the 3D finite element simulations of arc welding process. The influence of significant welding process; and heat source parameters on transient temperature histories, shape
and boundary of the FZ and HAZ is successfully demonstrated. Based on the investigations from the present research work, the following important conclusions can be drawn.

![Graph](image1.png)

**Fig. 16: Effects of welding speed on peak temperature transverse to weld direction**

![Graph](image2.png)

**Fig. 17: Effects of welding speed on peak temperature along the weld direction**
1. The results show that welding speed, heat source parameters and the total heat input to the plates can significantly affect the peak temperatures in the FZ and HAZ. Also the shape and boundaries of FZ and HAZ are sensitive to the changes in the input parameters.

2. GOLDAK’s heat source parameters distribution directly affects the boundaries and shape of the FZ and HAZ. The heat source parameters also significantly affect the peak temperature in FZ and HAZ.

3. The total heat input to the plates has obvious effects on peak temperature achieved in the FZ and HAZ. The change in temperature is approximately directly proportional to the heat input. Similarly, the increase in welding speed results in a decrease of the peak temperature in the FZ and HAZ.

NOMENCLATURE

\[ a_f \] Length of front ellipsoidal (m)
\[ a_r \] Length of rear ellipsoidal (m)
\[ b \] Width of heat source (m)
\[ c \] Depth of heat source (m)
\[ f_f \] Fraction of heat in front ellipsoidal
\[ f_r \] Fraction of heat in rear ellipsoidal
\[ Q_f \] Power density in front ellipsoidal (W/m\(^3\))
\[ Q_r \] Power density in rear ellipsoidal (W/m\(^3\))
\[ Q \] Total heat input (W)
\[ I \] Welding current (amperes)
\[ V \] Welding voltage (volts)
\[ \eta \] Arc efficiency (% age)

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