Three-Dimensional Finite Element Optimization of Bead Shape Developed 
During TIG Welding of Mild Steel
Sumanlal M.S., Sarin P, Joy Varghese V.M.
(Department of Mechanical Engineering, College of Engineering, Thiruvananthapuram, Kerala 695016.)

Abstract
In 1984 John Goldack [1] presented a double ellipsoid model for representing welding heat sources that has the capability of analyzing the thermal history of shallow, deep penetration and asymmetrical welds. This heat source model has been utilized by many researchers because of its capabilities to simulate welding heat transfer accurately in a simplified manner. This model consists of constants called heat distribution parameters which plays an important role in the accuracy of thermal simulation. In this study a range of values of these parameters were validated using 3D numerical simulation and the optimum values were found out by optimizing each parameter while the remaining are kept constant. Using the new optimized values optimum current for welding of mild steel plate is also obtained.

1. Introduction
Welding is a reliable and efficient metal joining process used in almost all industries like nuclear, aerospace and pressure vessel applications. In which arc welding is a popular metal joining process around the globe to produce high strength joints. It is a complex process in terms of control of temperature fields, strains, residual stresses, formation of cracks and their propagation. Due to the intense concentration of heat during welding, the regions near the weld line undergo sever thermal cycles which may lead to microstructural changes.

The exponential growths in computer technology, numerical methods and geometrical modeling have increased the capabilities of welding simulations. Numerical simulations have been used to understand the effect of different boundary conditions, weld parameters and weld processes on thermal, stress distribution and distortion on the base material. Researchers have developed different moving heat sources according to weld bead shape and heat flux distribution. One of the famous heat source model is John Goldack’s double ellipsoidal model [1] which is well renowned for its simplicity and accuracy.

1.1 literature survey
A heat distribution model will generate the magnitude and direction of heat flux distribution over the weld surface. Rosenthal in 1941 applied Fourier’s law to moving heat sources and developed a model that can be used to represent as point, line or plane sources of heat. This approach resulted in reasonable predictions of transient temperature fields at some distance from the heat source. Subsequent developments were proposed by other researchers and these leads to improved predictions for conventional arc welds. Pavelic in 1969 made improvements by representing the welding arc as a distributed surface flux. In order to account the effects of arc pressure and weld pool depression a model was proposed by Friedman in 1978, in which the heat source was represented as a volumetric distribution. A double ellipsoidal approach to representing welding heat sources was first proposed by Goldak et al. (1984) [1], has been widely adopted by researchers over the past thirty years. Goldak and co-workers proposed a non-axisymmetric heat source distributed in three dimensions in order to better account for the depression of the weld pool surface owing to the arc pressure. Sapabathy [2] introduced modified double ellipsoidal model with a differential distribution at the front and back portion of arc which is most suitable for even vibrating heat sources that can be used for modelling any type of welding technique including wave technique.

Numerical simulation has been an alternative to investigate in detail the effects of the arc on the heat input distribution of the welded plate, since the increase in the computer capacity has made it quick and inexpensive in the last years. The finite element method (FEM) has been widely used to deal with welding process problems which involve thermal, metallurgical and mechanical phenomena. Teng and Chang [1998] reported that the first thermo
A mechanical model was developed by Friedman [1975] using the FE method to calculate temperatures during welding. Temperatures and stresses were analysed by Karlsson [1989] and Karlsson and Josefson [1990] in single-pass girth butt welding of carbon-manganese pipe using the FE codes ADINAT and ADINA. Chen and Kovacevic [2003] have studied the thermal history and thermo mechanical process in the butt-welding of aluminum alloy 6061 – T6 through three-dimensional FE analysis, using the software ANSYS.

2. Welding Heat Source model

The double ellipsoidal heat source model proposed by Goldack is as shown in figure 1. The proposed heat source is composed of two ellipsoidal heat sources where one defines the heat input in the front and the other in the rear part of the ellipsoid. In the present study, the heat from the moving welding arc is applied as a volumetric heat source as in Figure 1. The equation for Goldak [1] heat source in \((x; y; z; t)\) coordinates can be written as:

\[
Q_{(x,y,z,t)} = \frac{6\sqrt{3} f \eta V I}{a b c \pi \sqrt{n}} e^{-3 \left(\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2}\right)}
\]

Where \(x, y\) and \(z\) are the local coordinates of the double ellipsoid model. \(f\) is the fraction of heat deposited in the weld region. \(V\) and \(I\) are the applied voltage and current respectively. \(\eta\) is the arc efficiency for the TIG welding process and assumed to be 70%, \(v\) is the speed of torch travel in mm/s and \(t\) is the time in seconds. The parameters \(a, b\) and \(c\) are related to the characteristics of the welding heat source which are found out by measuring the weld pool parameters.

Usually the heat source parameters \(a, b\) and \(c\) are obtained by solving the available empirical relations or by measuring weld pool dimensions. It was found out that the parameters thus found out are not accurate and leads to failure of simulation. Hence this study is an attempt to optimize these parameters by numerical iterations and to validate the optimized parameters using experimental results.

3. Numerical modelling

For the present analysis plate with dimension 100\(\times\)50\(\times\)12 mm as shown in fig.2 (a) is spot welded using TIG welding. The meshed model of plate is shown in fig.2 (b). The variable meshing is necessary to accommodate the localized heat flux, due to welding torch. The material used is mild steel and its temperature dependent thermal properties are taken from Dean Deng et al. [3].
4. Thermal analysis

Analysis is done for an un-grooved mild steel plate of length 100 mm width 50 mm and thickness 12 mm as shown in Fig. 2(a). Since the plate is symmetrical, half of the plate needs to be modeled. By using appropriate mesh optimization technique, relatively fine mesh is generated in and around the weld lines and comparatively coarse mesh is applied areas away from weld line as shown in fig 2(b). 8 node brick thermal element with temperature as degree of freedom is used for the thermal analysis.

The 3D heat conduction equation with heat generation is solved to find out the temperature profiles. The heat source used in the present study is a double ellipsoidal distribution which is applied as volumetric heat source over the weld plate. The plate is assumed to be open to atmosphere at all sides.

The combined convective and radiative heat transfer coefficient from Dean Deng et al. [3] as in equation [7] is used to apply boundary condition.

\[
h = 0.68T \times 10^{-8} \text{ (W/mm}^2\text{)} \quad 0 < T < 500 \text{ °C}
\]

\[
h = (0.231T - 82.1) \times 10^{-6} \quad T > 500 \text{ °C}
\]

Where \(h\) is the combined convective and radiative heat transfer coefficient, \(T\) is the temperature in °C. Transient thermal analysis is done for the above condition.

5. Validation of finite element model

For the validation of developed numerical model, an experiment was carried out using stationary TIG welding in the TIG welding machine and the temperature profiles were measured using the thermocouple. The experiment was carried out on a mild steel plate of dimension 100mm length 50mm width and 12 mm thickness. The thickness was fixed as 12 mm in order to avoid complete penetration during application of stationary welding torch. The plate was welded with 120A welding current and 12 V for 120s with gas flow of 40l/min. Thermocouples were fixed at 30 mm distance from the weld center-line at a depth of 10 mm from the top surface where the welding was carried out. The thermocouple was further connected to an Arduino board which was programmed to measure temperature. Figure 5.2 shows the comparison of measured and predicted temperature values.

The measured temperature values and the expected values are in good agreement. The maximum deviation in the predicted temperature values are less than 20 °C. It may be due to errors in the thermocouple measurement. From figure 5.2 it can be concluded that the developed finite element model can predict the thermal cycles successfully and it can be used for further studies on heat flow analysis during TIG welding.

Fig 3. Comparison of FEM results and Experimental results
6. Results and Discussions

6.1 Optimization of heat source parameters

The heat source parameters a, b and c mentioned in equation 1 are usually found out by solving empirical relation available for the particular welding method. For the optimization of the parameters one of the value is varied while the other two are kept constant. Likewise, all the three parameters are optimized. The analysis is conducted using an ANSYS APDL user subroutine. The input values are given through the subroutine command and the output value are measured manually after analysis. Heat source parameters for different welding current 100A, 120A, 150A and 180A are optimized by this method.

Fig.4 shows the applied input parameter and predicted weld pool dimensions for 100A spot welding current applied on a 12 mm plate. From Fig.4 it is observed that for all the three parameters there is a range of value over which input parameters and output dimensions are almost same. Hence this range of values are selected for further study.

![Fig 4. Iteration of welding parameter for 100A](image1)

![Fig 5. Heat source parameters for Different welding current](image2)
In the above iteration process for 100A it has been found out that the optimum values for a, b and c are 3.44, 3.40 and 3.82. For the further studies these values are used for the simulation. Likewise, the heat source parameters are calculated for different welding current ranging from 100A to 180A as in Fig5.

From Fig5 it can be seen that all the three parameters increase with increase in welding current. While observing variation of ‘a’ and ‘b’, it can be seen that, after 165A there is a variation, in the rate of increase.

6.2 Depth to width ratio for different welding current

Welding simulation were carried out to find out relation of depth to width ratio for different welding current. In the developed welding model, current is varied from 100A to 180A and the predicted depth to width ratio is measured for each current. The variation is as in Fig6. From Fig6 it can be observed that after 120A the depth to width ratio decreases with increase in current.

![Fig 6. Variation of depth to width ratio with welding current](image)

7. Conclusion

The FE model for welding of plate is developed and the temperature histories for plate surface along different axes were plotted. The heat source parameters a, b and c were found out by trial and error method by iteration and curve fitting of the results. Using the new heat source parameters simulation for different welding current was carried out and depth to width ratio was plotted. From the simulated results the following points can be concluded:

- From the simulated finite element model, heat source parameters were calculated by iteration for each welding condition.
- The temperature distributions after the weld source retraction are steady in nature.

- Depth to width ratio was found out to be maximum at 120A and after that the ratio decreases due to steep increase of heat parameter ‘a’ than ‘b’.

8. Reference


