Investigations of heat source models in transient thermal simulation of pulsed MIG welding of AA6061-T6 thin sheet

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Abstract. The automobile and aviation industries are exhaustively working on weight reduction by replacing steel with aluminium alloy. However, joining the aluminium alloy body panel is remain a big challenge because of the inherent properties of aluminium. The dynamic behaviour of arc plasma in the pulsed MIG welding process is a multifaceted heat mass transfer phenomenon involving chemical, electro-magnetic, and fluid dynamics. Numerical simulation using FEA techniques are greatly helpful in understanding responses of weld bead and material behaviour. Simultaneously it reduces time and cost consuming experimental trial and error approach. The approximation of the welding arc heat source is paramount for precise prediction in the welding process simulation model. The article focuses on the comparison, suitability and effects of various moving heat source models by developing the transient thermal simulation of pulsed MIG welding of 1mm thick AA6061-T6 sheet in ANSYS workbench. Moving heat source models were developed as ANSYS APDL command subroutine. It is observed that for 1mm thin sheets Gaussian surface heat source model is also valid. The difference in temperature field is not prominent in comparison with Goldak’s double ellipsoidal heat source model.

1. Introduction
Aluminium alloy was first time used during the 1980s in Mazda RX-7, Japan for its hood. Subsequently, Aluminium alloy sheets (AA sheets) swiftly used in sports cars, luxury sedans and the aviation sector. The application of aluminium alloy is growing at a moderate pace even after several advantages of the application of AA sheets in the automobile and aviation sector. The major reason for hindered growth is considerably different properties for joining compare to usual material steel. “Exceptional properties of aluminium alloy like, high thermal conductivity; high solidification shrinkage; oxide formation on the surface; high coefficient of thermal expansion; high solubility of hydrogen when in the molten state; and relatively wide solidification-temperature ranges which influence the aluminium welds and make it difficult to weld.” [1] On other hand, the application of AA sheet in the automotive, marine and aerospace sector is demanding exponential growth because of its recyclability, less weight, excellent strength to weight ratio.

Heat input, hydrogen solubility, welding of different grades and thickness are challenges in joining thin AA sheet. [2] MIG welding provides controlled heat input. It is the most preferred method for welding thin sheet at a lower temperature. However, a challenge in controlled steady molten metal
transport is an unfavourable factor for the MIG joining. Although higher ampere gives controlled spray metal transfer which provides a higher temperature that demands slow welding speed. The end of the 20th century witnessed phenomenal development in MIG welding techniques by researchers and implemented by industries. They utilized the pros of the MIG joining and reduced its process-induced cons by variation of the process. Pulsed MIG welding is successfully used for joining thin sheets by effective and synergic control. [3]

In the pulsed MIG welding process welding parameters have a significant role in developing quality weld bead. Identification of correct welding parameters demands exhaustive experiments which are time-consuming as well as costlier. Numerical simulation through finite element analysis (FEA) can be effectively used for evaluating the welding process. The phenomenal growth in computing technology has predicted the welding process and post-process through FEA. A good agreement between experimented and predicted FEA results is well established. Validation of the designed FEA problem is essential. Heat source modelling is prime input to the FEA of the welding process and selection of the correct heat flux distribution model is the key to the formation of the right FEA model. Comparative study of transient thermal analysis of various heat source models for fusion welding of the thin sheet is rare in the literature. The behaviour of a thin sheet of thickness 1mm is different than a thick sheet Therefore, an endeavour is made to develop a comprehensive transient thermal simulation model in FEA software ANSYS to investigate the effects of different heat source model in pulsed MIG welding of AA6061-T6 1mm thick sheet. The findings will add knowledge in the domain of numerical simulation of the joining process and selection of heat source model.

2. FEA Software
Since the mid of 20th-century, welding simulation is widely used. This simulation approach was programmed in FORTRAN, C, C Sharp and C++ programming tools. With the exceptional progress in computing technology, at present lots of FEA software exists. Simulation software are having integrated CAD Packages, advanced mesh techniques, and different packages of thermo-mechanical analysis. [4] FEA software which researchers have used for simulating the welding process can be summarized as follow.

- ANSYS (ANSYS Inc.),
- MATLAB (MathWorks),
- NASTRAN (MSC Software),
- COMSOL (COMSOL Inc.),
- ABAQUS (Dassault Systèmes),
- ArcWeld (ABB),
- WELDSYS (ESI Group)
- Virfac (ALTAIR) and
- MARC (Marc Analysis Research Corporation),

3. Heat source models
It is crucial to understand the way heat is supplied to the welded zone and heat flux is distributed in the welded zone. The dynamic behaviour of arc in the pulsed MIG joining is a complex heat mass transfer phenomenon. It involves chemical, electro-magnetic, and fluid dynamics. Moreover solid, liquid, gas and plasma condition of material found in tiny welding zone through simultaneous existence of thermal, mechanical, and electrical process as shown in figure 1. [4]

The optimum combination of pulse parameters in pulsed MIG welding gives high reliability of defect-free weld bead for the structural component. Trial and error method of setting up pulse parameters indeed not result in better combination and will end up to the poor quality of weld bead. Numerical simulation using FEA techniques reduces time and cost centric experimental trial and error approach. It helps in understanding responses of process variables over critical performance factors. The output of this simulation tools significantly depends on the provided transient thermal data of the process.
The simulation model builds by the provided data on surface heat flux model, right boundary conditions, accurate base material and filler material thermo-mechanical properties.

![Welding zone in the MIG welding process](image)

**Figure 1.** Welding zone in the MIG welding process

The heat source can be a point heat source, line heat source or plane heat source. Correct heat source model selection governs the efficiency of modelling of MIG welding of thin sheet. Many heat source distribution models were developed since the 1960s, such as “2D Gaussian surface heat source model, 3D Circular disc heat source model, Single ellipsoidal heat flux distribution, Double ellipsoidal heat source model, 3D Gaussian conical heat source model and Uniform surface heat flux model.”

| Heat source model | Gaussian surface heat source model | Double ellipsoidal heat source model | 3D Gaussian conical heat source model | Uniform surface heat flux model |
|-------------------|-----------------------------------|-------------------------------------|--------------------------------------|-------------------------------|
| Principle of model | Heat is dispersed as per the Gaussian curve path. | The heat source was divide into the front and rear sections, each of which separates heat flux distribution as shown in the figure has. | The conical shape represents the arc and for that reason rationale for demonstrating the welding process. Conical shape with compact lower cone radius of and large upper cone radius. | A Uniform surface heat flux model can be formed with a circular, square or rectangular heat source. It is an uncomplicated faster method for shallow penetration |
| Characteristic curve | ![Gaussian curve](image) | ![Double ellipsoidal curve](image) | ![3D Gaussian conical curve](image) | ![Uniform surface heat flux model](image) |
| Heat source description | \( Q(x, y, z) = Q_0 \exp\left(-\frac{x^2 + y^2}{r_c^2}\right) \) | \( q = \frac{\pi T_1 f_0}{\pi r_c^2} \exp\left(-\frac{x^2 + y^2}{a^2}\right) \) | \( Q_0 \exp\left(-\frac{x^2 + y^2}{r_c^2}\right) \) | \( \frac{Q}{\pi r^2} \) |
| \( Q_0 \) = Amount of heat introduced by the source, \( x, y, \) and \( r_c \) = geometrical parameters of the heat source position. | \( q_r = \text{Volumetric heat flux density in front and rear part of the model respectively.} \) | \( Q_0 \) = Maximum value of volumetric heat flux density \( r_c, r_i \) = upper and lower cone radius respectively \( z_c, z_i \) = cone length parameters, \( x, y, z \) = point coordinate | \( r = \text{radius of heat source} \) | \( Q = \text{Total introduced heat} \) |
| Suitability | This model is regularly applied in FEA of high power densities joining process i.e. laser, plasma, and microplasma welding | Widely used heat source model in commercial FEA software for arc welding. | It is suitable for simulations of deeper penetrating joining process like electron beam welding and laser beam welding. | It is similar to the Gaussian circular disc model, suitable for deep penetration. |
Out of this many approaches following four heat flux model are more appropriate for thin sheet MIG welding. As the thin sheet is representing a plain surface it is necessary to investigate differences between the 2D surface model and the 3D heat flux model. These four primary heat flux models are elaborated in Table 1.

4. Methodology
In the present study, FEA analysis of pulsed MIG welding of AA6061-T6 thin sheet is carried out using different heat source models in ANSYS R19.3. ANSYS Parametric Design Language (Ansys APDL) is used to develop subroutine command for different heat flux distribution models. Following table 2 narrate the details of parameters selected for the present transient thermal analysis. The FEA strategy adopted is as per the three-stage FEA viz. Preprocessing, Solution and Post-processing.

| Table 2. Numerical simulation details. |
|----------------------------------------|
| Material (Sheet metal) | AA6061-T6 |
| Thickness | 1.0 mm |
| Peak current | 45A |
| Background current | 15 A |
| Voltage | 15 |
| Welding speed | 0.0032 m/sec |

4.1. FEA assumptions
Following FEA assumptions are made while creating the FEA model.
1. The initial temperature of the FEA model is 28°C.
2. The thermo-mechanical properties of the AA6061-T6 are taken from the material library of ANSYS.
3. The pulsed MIG welding efficiency is considered as 75%.
4. Sheet metal surface convection effect is considered.
5. The molten metal weld pool flow is neglected.
6. Weld bead material is considered the same as AA6061-T6.
7. Weld bead is considered as part of the model.

4.2. Governing equations and heat source model
The source of energy is from arc plasma during the pulsed MIG Welding process. Heat conduction in the weld bead area is heat flux distribution from a hot area to a cold area. This can be presented as a linear relationship with temperature gradient and can be expressed as a partial differential equation as mentioned below.

\[
\frac{\partial}{\partial x} \left( k(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k(T) \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k(T) \frac{\partial T}{\partial z} \right) + q_i = \rho c \frac{\partial T}{\partial t}
\]

Where \( k, T, q_i, \rho, c, v, w \) represent thermal conductivity, temperature, external heat supplied to the body, density, specific heat of the medium.

In the present work, all four models as mentioned in table 1 is adopted for calculating heat flux. Comparison of the distribution of volumetric heat flux in each of the modelled is derived using the heat source description as mentioned earlier.

4.3. Preprocessing
A butt joint design is prepared to join two thin sheets of AA6061-T6 as per American Welding Society standard code AWSD9.1 in ANSYS space claim. [16] Fine meshing was done in a transient thermal analysis system. SOLID90 mesh element type was selected, as it is a higher-order version thermal element SOLID70. The element has 20 nodes with a single degree of freedom, temperature, at each
node as shown in figure 2. The solution o/p is in form of Nodal temperature included in the overall nodal solution. Fine meshing was done throughout the sheet metal as shown in figure 3, in which total 72117 nodes were created from 21928 elements for the analysis.

4.4. Solution - defining initial conditions and boundary conditions
The heat dissipation through convection is considered between sheet metal and surrounding as mentioned in Figure 4. The ambient temperature is considered as 30°C. Four temperature probes are placed on sheet metal as shown in Figure 5 for measuring and comparing temperature profile. Coordinate system origin is placed between two sheet metal and at the centre of the weld bead.

The moving heat source movement started from the origin of the coordinate system and ends at the sheet metal end on the z-axis. 
Welding parameters as mentioned in table 3 is considered while calculating arc power. 
Arc power = Q = ηV1 
Where V and I are the input voltage and mean current and η is welding process efficiency considered as 75%. The calculated arc power is fed as input to various heat source models for solving temperature distribution in a sheet while welding. The Gaussian surface heat source model is available as Ansys ACT extension by Ansys Inc., whereas the other three models were coded in ANSYS APDL.
Table 3. Welding parameters

| Peak current ($I_p$) | Background current ($I_b$) | Mean Current ($I_m$) | Voltage (V) | Speed (mm/sec) | Heat Flux (Joule/second) |
|----------------------|-----------------------------|----------------------|-------------|----------------|-------------------------|
| 45                   | 15                          | 30                   | 15          | 3.2            | 360                     |

5. Result and discussion

The transient thermal simulation was carried out to measure transient temperature distribution while pulsed MIG welding of AA6061-T6 thin sheet of 1.00mm. For measuring the temperature at various points on the sheet, the temperature probe was mounted at 7mm, 17mm, 27mm from the weld line and one probe is mounted on the weld line as shown in figure 5. Moving heat source moved with the input speed of 0.0032m/s in the welding direction over the weld line, simultaneously heat dissipation started over the sheet surface. Figure 6 depicts the temperature development on the entire four probes during the total movement of heat flux till the end of the sheet. The simulated temperature observed at various points on the sheet metal during the adoption of various heat source models is narrated in table 4.

Table 4. Temperature measurement

| Sr. No. | Model                                | Max. Temperature in °C |
|---------|--------------------------------------|------------------------|
|         |                                       | Probe 1 | Probe 2 | Probe 3 | Probe 4 |
| 1       | 2D Gaussian surface heat source model | 730     | 428     | 259     | 171     |
| 2       | Double ellipsoidal heat source model  | 802     | 587     | 370     | 251     |
| 3       | 3D Gaussian conical heat source model | 785     | 534     | 342     | 225     |
| 4       | Uniform surface heat flux model       | 819     | 596     | 357     | 231     |

It was observed that the maximum temperature on the weld line was observed in the uniform surface heat flux model. Whereas minimum temperature was observed in the 2D Gaussian surface heat source model because of consideration of surface plane only. However, the difference between these heat sources is marginal.

Figure 6. Temperature distributions at various probes
The heat-affected zone is large in the Double ellipsoidal heat source model. It can be said that the rate of reduction of temperature at probe 4 is minimum in the Double ellipsoidal heat source model. The temperature at probe 4 is 31.87% higher in Double ellipsoidal heat source model compare to minimum temperature at 2D Gaussian surface heat source model. Whereas in contrast temperature at probe 1 is only 8% higher in Double ellipsoidal heat source model compare to minimum temperature at 2D Gaussian surface heat source model. Therefore heat flux distribution is fast and the heat-affected zone is large in the Double ellipsoidal heat source model which is in agreement with experimental results of previous work. The development of heat affected zone can be easily predicted on the base of the temperature profile on the sheet metal at the end of the process. The temperature profile for the various heat source models is compared in figure 7. The heat dissipation pattern change as the heat source assumptions change. The elliptical temperature distribution pattern is visible in the double ellipsoidal heat distribution model whereas a small elliptical profile is visible in a 3D conical heat source model and a circular progressive temperature profile is visible in the other two models. The largest heat-affected zone with faster heat flux distribution is observed in the double ellipsoidal heat source model.

(a) Gaussian surface heat source model
(b) Double ellipsoidal heat source model
(c) 3D Gaussian conical heat source model
(d) Uniform surface heat flux model

Figure 7. Comparison of transient heat distribution profile

6. Conclusion

In this investigation of the heat source models, ANSYS APDL code is used for transient thermal simulation of the welding process. The 1.0mm thin AA sheet 2D heat source model stands valid because of the smaller thickness and good thermal conductivity of sheet metal. It was observed that the heat distribution pattern matched the heat source models because of the vital role of conduction in heat transfer during welding. The difference between the temperature profile of heat affected zone between the 2D heat source model and the 3D heat source model is trivial because of the very less thickness of sheet metal. However, 3D Goldak’s heat source result is having a good agreement with the past experimented data of the research article. The geometrical parameters of various heat source
models also play a vital role in deriving temperature profile. Such geometrical parameters validation with the actual welding process is necessary as results may vary significantly with change in geometrical parameters of the heat source model. Therefore extensive studies and experiments required for the validation and consideration of the temperature profile generated by various heat source models in the future.

7. References

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