# Transient thermal finite element simulation of moving gas tungsten arc welding on AISI 4340 aeronautical steel

Cite as: AIP Conference Proceedings **2283**, 020108 (2020); https://doi.org/10.1063/5.0025111
Published Online: 29 October 2020

N. V. Dhandapani, V. Dhinakaran, K. Krishnakumar, and V. Rajkumar

# Transient thermal finite element simulation of moving gas tungsten arc welding on AISI 4340 aeronautical steel

N. V Dhandapani[1], V. Dhinakaran[2], K. Krishnakumar[3] and V. Rajkumar[4, a)]

*[1]Department of Mechanical Engineering, Karpagam College of Engineering, Coimbatore, India.*
*[2]Department of Mechanical Engineering, Chennai Institute of Technology, Chennai, India*
*[3]Department of Metallurgical Engineering, PSG College of Technology, Coimbatore, India*
*[4]Department of Mechanical Engineering, PSG Institute of Technology and Applied Research, Coimbatore, India.*

[a)]Corresponding author: vrajkumarphd@gmail.com

**Abstract.** The study investigates on temperature distribution of moving heat source performed on a coupon. Heat dissipation and penetrationcharacteristics are being investigated. Finite element solution of a moving heat source model is attempted by using ANSYS. Transient thermal analysis model was chosen to achieve heat input characteristics for the model. Volume of welding process, voltage and current were the parameters considered in designing the heat source. Heat source was formulated using Gaussian heat equation. The heat source was introduced on plates of different thicknesses (3mm, 4mm, 5mm and 8mm) and was found that the heat dissipation characteristics changed in accordance with the thickness of the coupons. The study suggests that the trial welds and bead on welds should be done on samples with similar thicknesses as it directly affects the metallurgical characteristics of the weld.

## INTRODUCTION

The solution on analysis of heat source models especially in welding has been under investigation for the past few decades.Theoretical and finite element investigations for the perdition of effect of temperature and other thermal attributes of moving heat sources are most important tools for validation of experimental results(1). Critical input functions namely: electric current and welding speed and electrode diameter as a function of ellipsoidal heat source are few of the important factors generally considered for analysis (2).

The temperature gradient and thermal expansion during heat input to a metal during welding depends on the welding process and the control parameters aforementioned. The size and shape of weld puddle developed and temperature distribution seemed more precise based on Gaussian distribution technique. Eventually the same has become the important parameter for analyzing temperature affected areas in welded coupons for designing weld joints (3).Discrete element analysis was used in a formulation of transient a mathematical multi dimensional model in both 2D and 3D for investigating both conduction and convective heat transfer problems simultaneously pertaining to moving arc welding sources. The results of the investigation clearly emphasized on influence of the heat and fluid flows and the geometry of specimen on the development of the weld (4).

The development of mathematical model of travelling heat source was made only in recent decades, after which many attempts have been made on precise simulation of welding heat sources. A mathematical model has been attempted in order to consider for convection and temperature distributions in moving heat models controlled by electromagnetic, surface tension forces and buoyancy. Macro segregation of the solute content in the weld was discussed in view of computed results on convection in weld pool (5). An approximate analytical solution for ellipsoidal heat source was developed for finite thick plates and the inventors claimed that shall directly be used for simulation in welding (6).Finite element method was applied in simulating a three dimensional autogenous gas tungsten arc welding of beta- titanium alloy. Transient heat distributions along the heat affected zones of the simulated welds were predicted by considering surface heat flux and conventional heat losses in welded coupons (7).

*Proceedings of International Conference on Recent Trends in Mechanical and Materials Engineering*
AIP Conf. Proc. 2283, 020108-1–020108-6; https://doi.org/10.1063/5.0025111
Published by AIP Publishing. 978-0-7354-4013-5/$30.00

In an attempt, the arc heat input was applied in the weld zone using various forms namely: surface, volumetric and combined heat flux distribution functions (8).

Estimation of residual stresses on inner and outer surfaces and along radial direction computed increase in temperature gradient and longitudinal and circumferential residual stresses of welding speed and power (9). In another finite element simulation process variables were related to melting efficiency through heat energy input rate. On comparing the values of experimental and simulations of previous results, it was found that Gaussian model was better than double ellipsoidal heat function (10).

On the basis of tridimensional gauss distribution of power density a double ellipsoidal heat source model was developed. Temperature field was estimated using both general and double ellipsoidal heat sources and were reported that heat source of the latter were in good agreement with experimental results (11). In another attempt, moving heat models by transient heat analysis by finite element method were employed to estimate weld thermal cycles and sections of isotherms obtained of gas tungsten arc welding of Inconel 718 coupons. In addition it was inferred that double ellipsoid model gave better results than Gauss model (12).

In a similar investigation by researchers, validations on shape of fusion zones obtained experimentally for various plate thicknesses (3, 4, 5 and 6mm) were done with the simulated results. The increase of s, radial distance of centre of heat source deteriorated the heat intensity but had an increasing and decreasing effect on the bead width and depth respectively except for higher values of s (13).

Two ellipsoidal heat sources were combined in an attempt, as the temperature gradient in the front side was not much steeper as expected but at the trailing edge were steeper than experimental results. The front and rear half were the quadrants of two ellipsoids. They also observed that the weld bead profiles were more appropriate and controlled with pulsed current mode welding, most importantly cooling rate being faster which is due to absence of arc during pulsing (14-15).

Generally bead on trails are performed by researchers depending on the application and service environments. However there is a possibility that the coupons used in the same may not be of uniform thicknesses due to difficulty in machining and/or other factors. This analysis is done in order to analyze if there are changes in heat dissipation pattern when a material is being welded. This study stands useful in understanding the importance of the above problem and provides insight in understanding material behavior during welding.

## METHODOLOGY

The surface Gaussian heat source model is generally used for thin plates, where the distribution along the thickness is not important. Therefore, this study considers its accuracy in welding processes of plates with various thicknesses. Analyses are performed by the ANSYS software, considering the convection and the radiation phenomena.

### Thermal analysis Equations:

During the welding process, the thermal field is governed by the heat conduction equation given by:

$$\frac{\partial}{\partial x}\, k(T)\frac{\partial T}{\partial x} + \frac{\partial}{\partial y}\, k(T)\frac{\partial T}{\partial y} + \frac{\partial}{\partial z}\, k(T)\frac{\partial T}{\partial z} + Q_V = \rho\,(T) C_P(T)\frac{\partial T}{\partial t}$$

Where T is the temperature,k(T) is the thermal conductivity,ρ(T) is the specific mass,
$C_P$(T) is the specific heat and$Q_V$ is the volumetric heat flux.

The thermodynamic boundary conditions on the external surfaces of the solid comprise heat transfer for convection and radiation. The heat flow density for convection ($q_c$) in the environment gas or liquid is given by Newton's heat transfer law:

$$q_c = h_c(T - T_o)$$

Where "T" is the temperature of the external surface,$T_o$ is the temperature of gas or liquid and $h_c$ is the coefficient of convective heat transfer. This coefficient depends on the convection conditions on the solid surface, besides the properties of the surface and the environment. The proposed values of coefficient of convective heat transfer are from 15 to 25 W/m$^2$K. The heat flow density for radiation $q_r$ is governed by the Stefan-Boltzmann law, as follows:

$$q_c = \varepsilon_r \sigma_r (T^4 - T_o{}^4)$$

Where"ε" is the emissivity of the material surface and $\sigma_r$ is the Stefan-Boltzmann constant.

The value of the emissivity depends on the temperature in the welding process in which it ranges from room temperature to approximately 1450°C. In general, higher the temperature, the larger is the emissivity. In this study, the heat of the welding arc with plate was modeled by a traveling three-dimensional distribution of heat source with a Gaussian distribution. Therefore, the heat flux and temperature distribution on the surface of the solid is related to the radial position.

## Meshing

Constant strain triangle mesh was adopted for the simulation. As it is linear model being investigated, four node rectangular (quad) elements were used for the simulation. Unifrom Contour plot distribution is achieved due to employing the above element. Material used in the analysis corresponds to AISI 4340 medium carbon steel whose chemical composition is given in the table below.

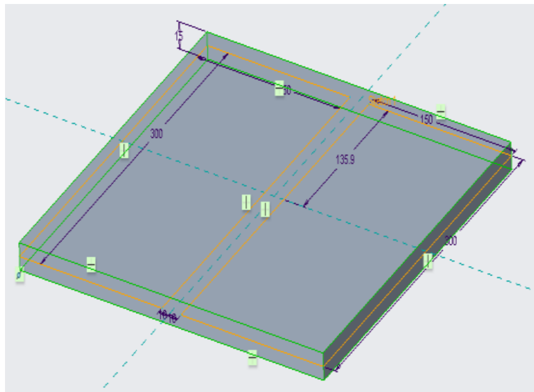
TABLE 1. Chemical composition of AISI 4340 medium carbon steelused in the analysis

| Element | Composition by weight |
|---|---|
| C | 0.38 |
| Ni | 1.65 |
| Mo | 0.2 |
| Mn | 0.6 |
| Cr | 0.95 |
| Si | 0.18 |
| Fe | 95.9 |

# RESULTS AND DISCUSSION

## Simulation

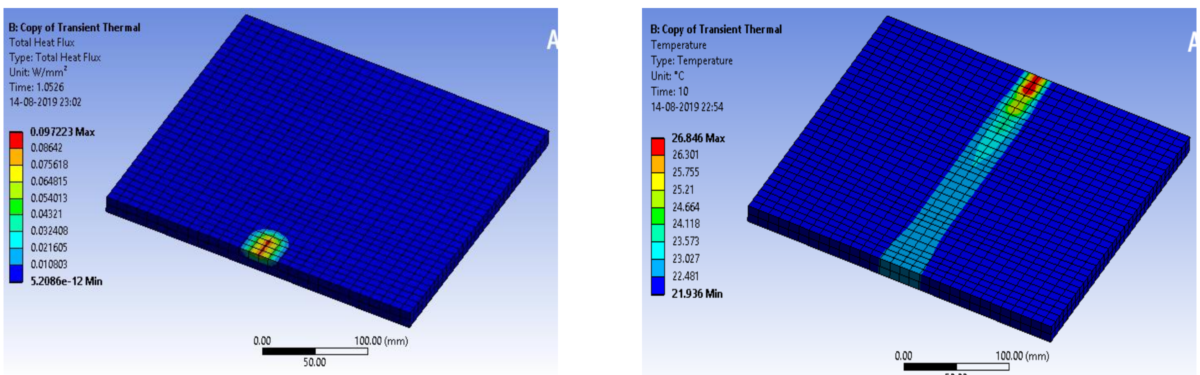
An improved version of estimation on temperature distribution near heat source area in (x,y and z) plane is analyzed. The solution is implemented to find out temperature distribution along a specific direction and about an axis. An analytical solution for transient temperature distribution for welded joint based on similar Gaussian heat distribution for different distribution and parameters was introduced of the semi-infinite body subjected to 3-D power density moving heat source. Figure 1 shows the 3D CAD model that was used for the simulation.



(a)

**FIGURE 1.** 3D CAD model geometry used for transient thermal analysis

The accuracy of the Gaussian heat source model was investigated through bead-on-plate weld trials. Transient thermal analyses were performed using ANSYS software, considering the convection phenomena. Numerical simulation was carried out on the coupontheoretically for various plate thicknesses viz: 3 mm, 4 mm, 5 mm and 8 mm.




(a) (b)

**FIGURE 2.** Showing (a) Isotherm initiated at the beginning of the coupon and (b) complete geometry of the isotherm at the end of the coupon

For most applications the material thicknesses used for study is between 3 to 5mm. However an attempt has been done in this research to analyze the heat conduction for coupon of higher thickness of 8mm as well for comparison. The simulation was paused at the centre of the coupon viz 50 mm from the beginning point and the isotherm was analyzed for its cross sectional pattern. Figure 3 shows the heat dissipation pattern when the heat source at the top of the coupons of different thicknesses. It can be ascertained from the same that the heat conduction is not identical in all the cases. The temperature attained from the heat source is in the order of 2800ºCelsius. It is evident from Fig.3 (a-d) that as the height of the sample thickness increased; the heat conduction rate has also increased. For the same arc speed of (mm/min) and material property, the heat conduction characteristics of the coupons show varying trend. The values of temperature at the top of the coupon indicate values of 2435ºC, 2155ºC, 2047ºC and 1913ºC.This is due to the fact that the heat source is transient and moving. Hence, the material depending on the thickness and speed of the moving heat source has dissipated heat in the aforementioned fashion which is highly agreeable and depicts precision of the analysis performed. However, it could definitely be ascertained that there will be change in the metallurgical characteristics between the samples which are being analyzed. Heat affected zones and especially the hardness profile of the welded specimens may show phenomenal variations which has a major effect on the weld strength.

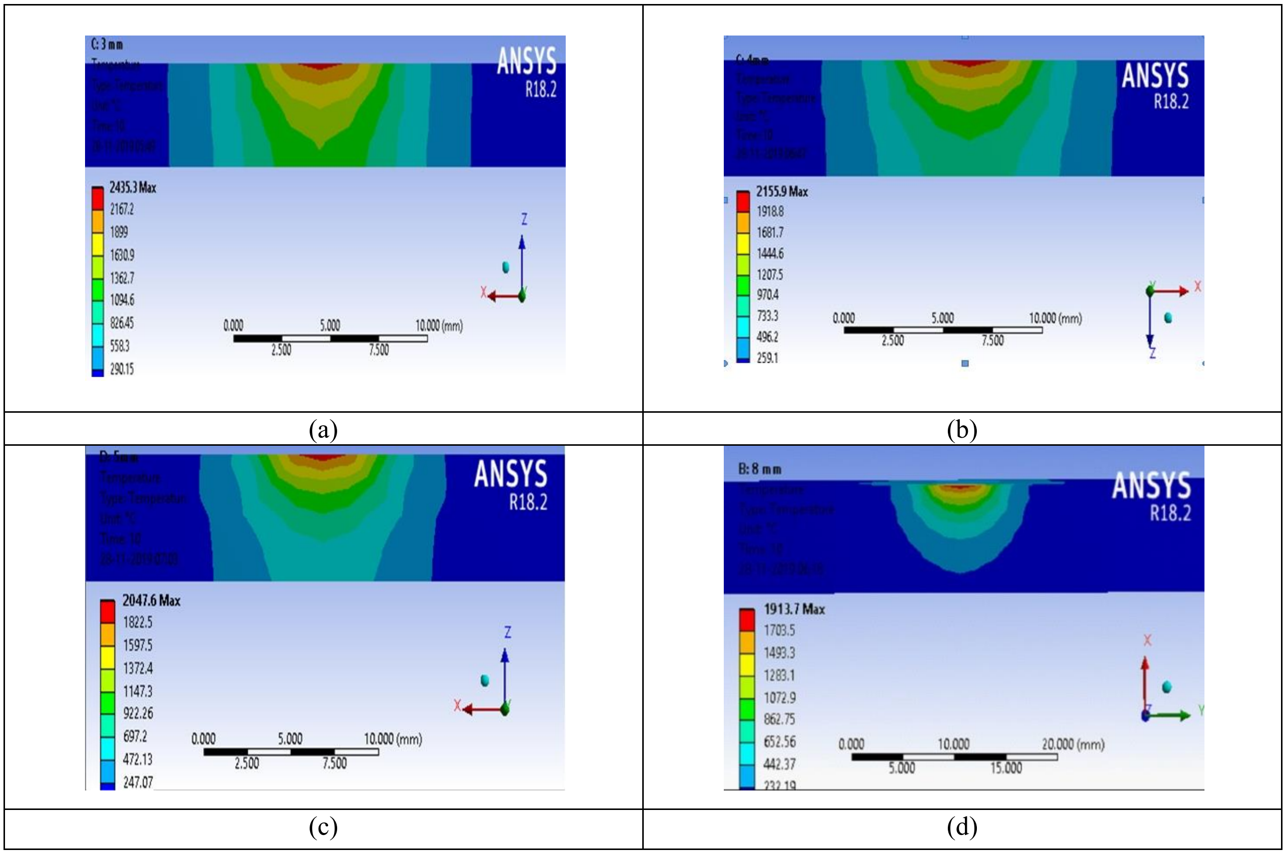



**FIGURE 3.**Showingheat conduction pattern in AISI 4340 samplesof thicknesses of (a) 3mm (b) 4mm (c) 5mm (d) 8mm

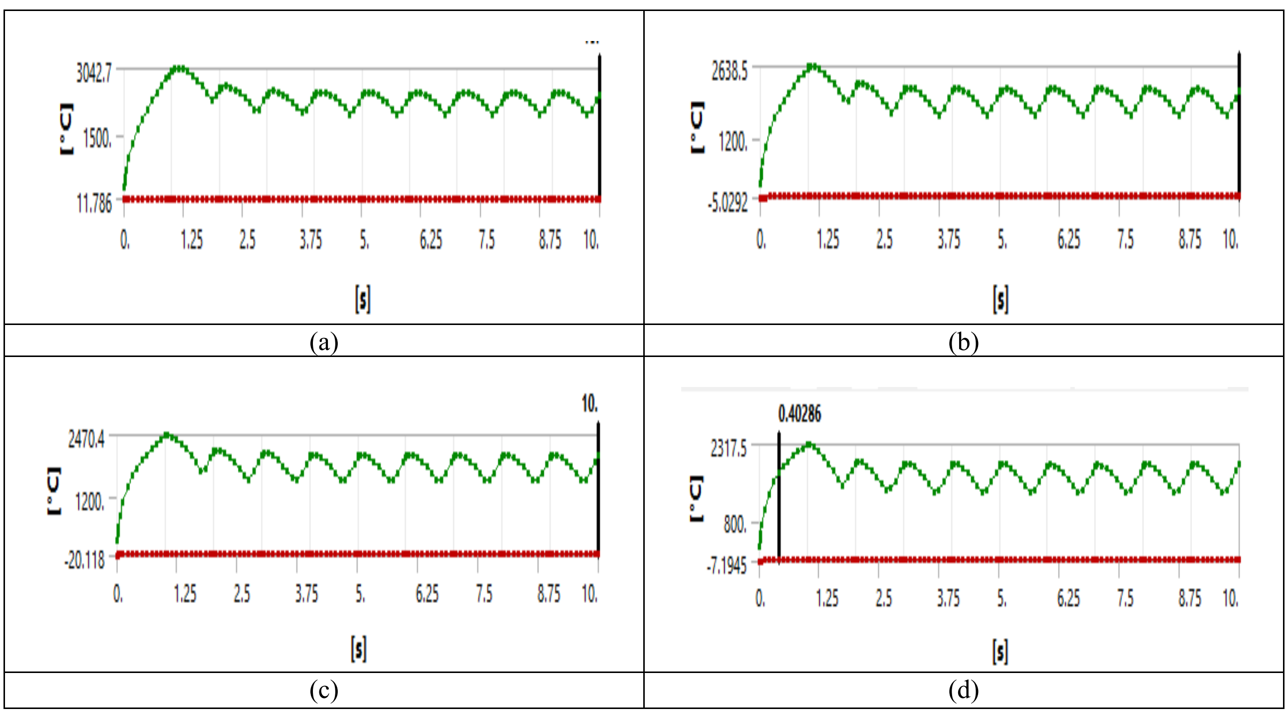



**FIGURE 4.**Showingplots of thermal cyclesobtained inwelding simulation for (a) 3mm (b) 4mm (c) 5mm (d) 8mm thicknesses

Figure 4 shows the thermal cycles of the simulated samples. It is observed that the temperature is stabilized very soon after the start of the weld (in about 1.25 sec). It is also observed that the as the thickness of samples increased from 3mm to 8mm, the maximum heat at the coupon is decreased. This can be attributed to the fact that coupons with less thickness conduct heat less than the coupons with higher thickness.

## CONCLUSIONS

The simulation of bead on trials has been precisely attempted in this study. The weld parameters have been precisely input to attain precise results. On running the simulation, and analyzing the cross sections of the sample, it can be concluded that for the same welding speed, as the thickness of the samples increased heat dissipation or convection in the weld pool shows a varying trend. As sample thickness increased, heat convection has decreased owing to smaller heat affected zone. This attempt shows evidently that finite element based simulation of experimental trials by Gaussian heat source model is very important for validation. It gives phenomenal insights to the researchers on the material behavior and realistic aspects. Therefore such a study is certainly required for successful optimization of welding parameters for service conditions.

## REFERENCES


1. J. Goldak and A. Chakravarti, A New Finite Element Model for Welding Heat Sources(Metallurgical Transactions B, Process Metallurgy, 1984), pp.299-305.
2. V. Pavelic and R. Tanbakuchi, Experimental and Computed Temperature Histories In Gas Tungsten Arc Welding Of Thin Plates(Welding Journal Research Supplement, 1969), pp. 295s-305s.
3. R.L. Ule, and Y.Joshi Y, A New Technique For Three Dimensional Transient Heat Transfer Computations Of Autogenous Arc Welding(Metallurgical Transactions 21B, 1990), pp.1033–1047.
4. T. Zacharia, and A.H. Eraslan, Three-Dimensional Transient Model For Are Welding Process(Metallurgical Transactions, 2014), pp. 645-659.
5. S. Kou and Y.H. Wang, Weld Pool Convection and Its Effect(Welding Journal, 1986), pp. 63-70.
6. N.T Nguyen and A. Ohta, Analytical Solutions for Transient Temperature of Semi-Infinite Body Subjected To 3-D Moving Heat Sources(Weld Journal, 1998), pp.265–274.
7. S. Vijay Rathore and K Balachandar, Three-Dimensional Finite Element Simulation Of Gas Tungsten Arc Welding For B-Titanium Alloy(Journal of Engineering Manufacture, 2014), pp. 730–735.
8. Dhinakaran, V., N. Siva Shanmugam, and K. Sankaranarayanasamy. "Some studies on temperature field during plasma arc welding of thin titanium alloy sheets using parabolic Gaussian heat source model." Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 231,695-711 no. 4 (2017).
9. A. Ravisankar, Satish Kumar Velaga, Influence Of Welding Speed And Power On Residual Stress During Gas Tungsten Arc Welding (GTAW) Of Thin Sections With Constant Heat Input: A Study Using Numerical Simulation And Experimental Validation(Journal of Manufacturing Processes, 2014), pp. 200–211.
10. E. A. Bonifaz**,** Finite Element Analysis of Heat Flow in Single-Pass Arc Welds (Welding Research Supplement, 2000), pp. 125-s.
11. Fang Hongyuan and Meng Qingguo, New General Double Ellipsoid Heat Source Model (Science and Technology of Welding and Joining, 2005), pp. 361-368.
12. RR Gokulakrishnan Sriram, V. Dhinakaran, Jagadeesha T " Finite Element simulation of Temperature Distribution and Residual Stress in Single Bead on Plate Weld Trial using Double Ellipsoidal Heat Source Model" International Journal of Recent Technology and Engineering 8, no. 1S2(2019): 133-138
13. R. F. Paulo Teixeira and Douglas Bezerra de Araújo, Study Of The Gaussian Distribution Heat Source Model Applied To Numerical Thermal Simulations of TIG Welding Processes (Ciência&Engenharia Science & Engineering Journal, 2014), pp.115-122.
14. N. Karunakaran and V. Balasubramanian, Transient Three Dimensional FE Modeling for Thermal Analysis of Pulsed Current Gas Tungsten Arc Welding of Aluminum Alloy(International Journal of Mechanical and Mechatronics Engineering, 2013), pp. 484-491.
15. N. Karunakaran and V. Balasubramanian, Multipurpose Three Dimensional Finite Element Procedure for Thermal Analysis in Pulsed Current Gas Tungsten Arc Welding of AZ 31B Magnesium Alloy Sheets (International Journal of Mechanical and Mechatronics Engineering, 2011), pp. 551-558.