Numerical Prediction of Weld Bead Geometry in Plasma Arc Welding of Titanium Sheets Using COMSOL

V. Dhinakaran*, Suraj Khope, N. Siva Shanmugam & K. Sankaranarayanasamy

**Department of Mechanical Engineering, National Institute of Technology,
Tiruchirappalli -620 015, Tamil Nadu, India,*dhinakaran.veeman@gmail.com**

Abstract: Plasma Arc Welding (PAW) is one of the important arc welding processes used in electronics, medical, automotive and aerospace industries due its high accuracy and ability of welding any hard materials. Though PAW is more complex and requires more expensive equipment compared to other commercial arc welding processes, it finds application in automotive sectors. In automotive applications, titanium metal is used particularly in motorcycle racing, where weight reduction is critical while maintaining high strength and rigidity. Titanium is in the group of reactive metals, which means that they have a good affinity for oxygen and readily forms an oxide layer leads to oxygen embrittlement. Therefore, the welding of titanium sheets is still an emerging technology in automotive sectors. The present investigation deals with the numerical simulation of plasma arc welding of 2 mm thick Ti-6Al-4V alloy using Finite Element code COMSOL. A Modified Three Dimensional Conical (MTDC) heat source model and a newly developed heat source model are considered for performing the numerical simulation to predict the temperature distribution on thin sheets of titanium alloy. The temperature dependent material properties of Ti-6Al-4V such as thermal conductivity, specific heat and density are used for performing the numerical analysis. Based on the results, it is observed that the predicted weld bead geometry from the temperature distribution plots using newly developed heat source model is in good agreement with the corresponding experimental result.

Keywords: Plasma Arc Welding (PAW), Heat source Model, COMSOL, Titanium

1. Introduction

Ti–6Al–4V is an alpha–beta alloy has excellent combination of properties such as low density, high specific strength and corrosion resistance, and it has been considered as one of preferred engineering materials extensively used in many industrial fields, accounting for more than 50% of all titanium tonnage in the world. Till date, no other titanium alloy threatens its dominant position. The aerospace industry accounts for more than 80% of this usage. The next largest application of Ti-6Al-4V is medical prostheses, which accounts for 3% of the market. The automotive, marine and chemical industries also use small amounts of Ti-6Al-4V [1]. In order to understand the concept of arc welding of titanium, a thorough literature survey has been made. There are several methods used to join titanium and titanium alloys in automotive sectors. Since Plasma arc welding is capable of producing deep penetration and low cost joints, it is being used to join titanium and titanium alloys. Developing a heat source for reflecting the thermo-mechanical process in plasma arc welding is key problem in Finite Element Simulation. C.S.Wu *et al.* developed a Modified Three dimension conical heat source model and Quasi steady state PAW heat source to reflect the thermo mechanical process of PAW. MTDC heat source model was implemented for the material having higher thickness [2]. A conical heat source model was used to simulate the relationship between welding parameters and welding efficiency and proposed that the relationship is useful for selecting combination of weld parameters and keyhole welding [3]. Short et al developed parametric envelope for Keyhole PAW of Ti-6Al-4V of sheet thickness of 2.1 mm [4]. Based on the literature survey, it is inferred that only limited amount of research work has been carried out by the researchers in the areas of numerical simulation and experimental studies related to plasma arc welding of thin titanium alloy sheets. Hence, an attempt is made through this research work to develop a new heat source model and simulate the plasma arc welding of titanium alloy sheets. The simulation results are compared with the experimental outcomes for validation.

2. Numerical Modeling

The regular procedure of arriving at welding parameters through experimental welding trials may not be suitable for costly materials such as titanium. Numerical modeling using FEM to simulate the welding conditions is one of the best alternatives to these costly trials. Numerical prediction of weld bead geometry i.e. bead width and depth of penetration of Plasma Arc Welded Ti-6-Al-4V sheet is presented here.

2.1Assumption

Some simple assumptions are considered to develop the Finite Element Model

i) The plasma arc is moving with a constant speed over the work piece

ii) Material properties like thermal conductivity, specific heat and density are temperature dependent.

2.2. Governing Equation

A heat transfer model is developed in order to simulate the plasma arc welding process in a moving coordinate system. The transient nonlinear thermal heat conduction equation given below describes the temperature (T) of the weld plate as a function of time (t) and spatial coordinates (x, y, z)

$$\rho C_p \frac{\delta T}{\delta t} + \rho C_p(-v)\frac{\delta T}{\delta x} = \nabla.(k\nabla T) + Q \quad (1)$$

Where k thermal conductivity in W/m.K, ρ is density in kg/m^3, C_p is specific heat in J/kg.K, Q is intensity of heat source , *v* is the speed with which heat source is moving on the plate in mm/s.

2.3. Heat Source model

In finite element simulation primary importance is to be given in selecting the appropriate heat source model to simulate the welding process. The plasma arc welding process is a high density welding process like laser beam welding and Electron beam welding. The Modified Three Dimensional Conical heat source proposed by CS.Wu [2] and a newly developed heat source model are used in this study to simulate the plasma arc welding process.

The heat flux distribution at any plane perpendicular to the z axis [2] can be represented as

$$Q(r,z) = Q_0 \exp\left(-\frac{3r^2}{r_0^2}\right) \quad (2)$$

Where Q_0 is the maximum heat intensity value, r_0 is the distribution parameter along radial direction.

In MTDC heat source model, the distribution parameter r_0 is given by

$$r_0(z) = a\ln z + b \quad (3)$$

Where

$$a = \frac{r_e - r_i}{\ln z_e - \ln z_i} \quad (4)$$

$$b = \frac{r_i \ln z_e - r_e \ln z_i}{\ln z_e - r\ln z_i} \quad (5)$$

Where r_e is the top radius, r_i is the bottom radius of the volumetric heat source, z_e and z_i are the z coordinates of the top surface and bottom surface respectively.

The value of maximum heat intensity is given by

$$Q_0 = \frac{3\eta VIe^3}{A_v\pi(e^3-1)} \quad (6)$$

Where

$$A_v = a^2\lfloor (H+z_i)\ln^2(H+z_i) - z_i\ln^2 z_i \rfloor - 2a(a-b)$$
$$\left[H+z_i)\ln(H+z_i) - z_i\ln z_i - H\right] + b^2 H \quad (7)$$

and $H = z_e - z_i$, $h = z_e - z$

Hence the expression for the distribution parameter is given as

$$Q(r,z) = \frac{3\eta UIe^3}{A_v\pi(e^3-1)}\exp\left(-\frac{3r^2}{r_0^2}\right) \quad (8)$$

The new model proposed in this research assumes the value of r_0 (z) to be parabolic and is given by

$$r_0(z) = a\,z^2 \quad (9)$$

Hence the value of maximum heat intensity for newly developed heat source model is given by

$$Q_0 = \frac{3\eta VIe^3}{A_v\pi(e^3-1)} \quad (10)$$

Where

$$A_v = (a^2/5)\lfloor (H+z_i)^5 - z_i^5 \rfloor \quad (11)$$

2.4. Initial and Boundary Condition

The initial condition and boundary condition have to be specified to solve the governing differential equation. The heat is exchanged between the weld plates and surrounding and consequently the welded plate is cooled by convention and radiation.

Initial condition is represented as a function of spatial coordinates only.

$$T(0,y,z,t) = T_{\infty}(x,y,z,t) \qquad (12)$$

The boundary condition for the top surface for convention and radiation is given by

$$-n.(-k\nabla T) = \varepsilon\sigma(T_{amb}^{4} - T^{4}) + h.(T_{amb} - T) \quad (13)$$

Where ε is the emissivity of the surface and is taken as 0.8 for Ti-6Al-4V alloy, σ is Steffen –Boltzmann constant and is taken as 5.67 x 10^{-8} W/m^{2}K^4,T_{amb} is the ambient temperature and is taken as 303 K, *h* is the convective heat transfer coefficient.

Table 1. Temperature Dependent material properties [5]

Temp. (K)	K (W/m.K)	C_p (J/kg K)	ρ (kg/m^3)
298	7	546	4420
373	7.45	562	4406
473	8.75	584	4395
573	10.15	606	4381
673	11.35	629	4366
773	12.6	651	4350
873	14.2	673	4336
973	15.5	694	4324
1073	17.8	714	4309
1173	20.2	734	4294
1273	22.7	643	4282
1473	22.9	678	4252
1573	23.7	696	4240
1673	24.6	714	4225
1773	25.8	732	4205
1873	27	750	4198
1923	28.4	759	4050
1973	33.4	830	3886
2100	34.6	830	3818
2200	34.6	830	3750
3500	34.6	830	3750

2.5. Material Model

The candidate material for the present investigation is Ti-6Al-4V sheet. During plasma arc welding temperature gradient is developed in the weldment from beginning to end of the process. Use of temperature dependent material properties will give the better temperature distribution in the process [6]. The FE code COMOSL has provision to add the temperature dependent material properties for simulation.

3. Experimental Work

Ti-6Al-4V alloy with the dimension of 200 x 100 x 2 mm is used to conduct the experimental trials. The chemical composition of the above said material is given in Table 2. Oxide layers and contaminations are removed from the surface of the plate by wire brush before welding and it is further cleaned with acetone.

Table 2. Material Properties

Component	Al	Fe	O	V	Remaining
Weight %	6	0.25	0.2	4	Ti

Figure 1. Plasma arc welded Ti-6Al-4V sheet – bead-on plate

Bead-on plate experiment trial is conducted using Fronius magic wave 4000 plasma arc welding machine with Direct Current Electrode Negative (DCEN) mode. The welding speed is controlled by CNC work station which gives uniform welding speed. The substrate material is clamped in a special fixture which has provision to provide an inert atmosphere under the substrate (bottom purging). Titanium has great affinity of interstitial elements like oxygen, nitrogen and absorbs them readily at elevated temperature. To avoid the reaction with environment the molten pool is protected with a special custom made fixture which is attached with the plasma torch and acts as trailing shields. Industrial pure Argon (99.9%) is used as a shielding gas to prevent atmospheric contamination of weld metal during plasma arc welding process. The color of the titanium weld provides an indication of the effectiveness of the inert gases on protection of the solidified weld metal from the atmospheric gases.

Figure 1 shows the top surface of bead-on plate trial of plasma arc welding of Ti-6Al-4V sheet. It is evident from the figure that the weld looks like bright silver indicates that there is no reaction with atmospheric gases during the cool down period and during the actual welding. The welding input process parameters used for producing a bright silver weld are listed in Table 3.

Titanium alloy has relatively very low thermal conductivity compared with other materials which cause local overheating. To prevent the local heating effort should be taken while cutting the titanium specimen. Cutting is done with Electric Discharge wire cut machine which uses water cooling to prevent local overheating. Standard mechanical polishing procedure is used further to prepare metallographic sample and etched with Kroll’s agent which is the excellent etchant for titanium and its alloy. The volumetric combination of etchant is of 2% of HF, 3% of HNO_3 and 95% of water. The macrostructure of the weld seam is characterized by welding Expert system and software.

Table 3. Welding input Parameters

Current (A)	60 A
Voltage(V)	20.8
Travel Speed	300 mm/min
Arc Length	80 mm
Torch shielding gas flow rate	12 LPM
Trailing shielding gas flow rate	20 LPM

4. Finite Element Analysis

In this work, a finite element model is developed using finite element code COMOSL multiphysics similar to the plate dimension 200 x 100 x 2 mm used for experimentation. Figure 2 shows the Finite Element model of 2 mm thin Ti-6Al-4V sheet (35893 nodes and 8047 elements). The center portion of the mesh model (along the length direction) is selected as the weld path. Since the fusion zone and Heat affected zone are anticipated with high thermal gradient and heal flux, fine meshing is done about 10 mm on the both sides of the weld path. Equation-based modeling in Heat transfer module under COMSOL Multiphysics is utilized to introduce the developed heat source equations in the FE model for simulating the plasma arc welding on titanium sheets. This enables the use of time-dependent loads and sources during the process. A time dependent nonlinear heat transfer analysis is run by applying initial and natural boundary conditions to simulate the temperature distribution profiles for predicting the weld bead geometry.

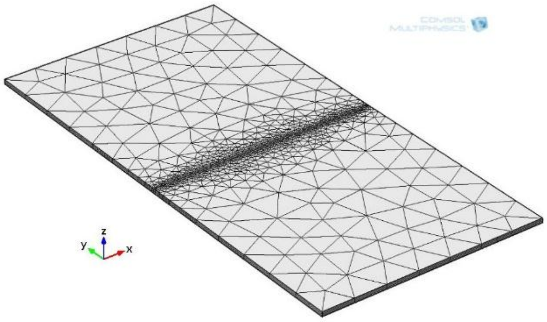


Figure2. 3D FE model.

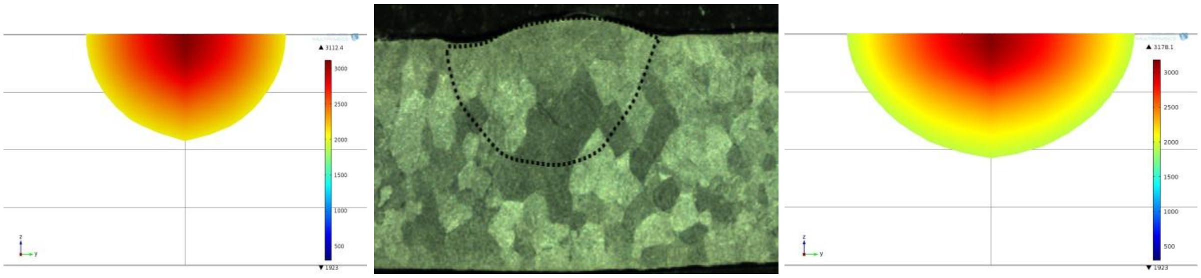
5. Results and Discussions

Temperature profile is computed using finite element simulation. Heat source parameters considered for performing numerical calculation are presented in Table 4. The simulation is carried out using two different heat source models i.e. Modified Three Dimensional Conical heat source and newly developed heat source. The efficiency of the plasma arc welding process is taken as 0.5 [3].

Table 4. Heat source Parameters

Parameter	Value	Unit
r_e	1.38	mm
r_i	0.001	mm
$H=z_e-z_i$	1.04	mm
Speed	300	mm/min
Efficiency (η)	0.5	---

Figure 3. Shows the macrograph obtained from MTDC heat source, Experimental and newly developed heat source. It is seen that the FE predicted fusion zone using newly developed heat source gives a reasonably good correlation with experimental macrograph.



(a) (b) (c)

Figure 3. Macrograph (a) MTDC (b) Experimental (c) Newly developed heat source

Table 5 shows the comparison of weld bead parameters observed by both Modified Three Dimensional Conical Heat source and newly developed Heat source. It is found that the weld bead geometry predicted by newly developed heat source model gives reasonably good accuracy than the weld bead geometry predicted by MTDC.

Table 5. Comparision weld bead parameters

Parameter	Bead Width	Depth of Penetration
MTDC	2.0 mm	0.9 mm
Experimental	2.75 mm	1.07 mm
Newly Developed Heat Source	2.5 mm	1.05 mm

Figures 4-10 shows the results of simulation performed with newly developed three dimensional heat source models.

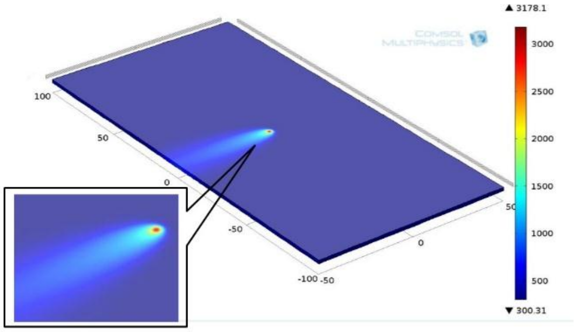


Figure 4. Temperature distribution at the middle of the plate

Figure 4 shows the temperature distribution at the middle of the plate. Figures 5-7 show the welding process i.e. the temperature distribution at different timings. Figures show that thermal gradient is high at the heat source location and steep temperature gradients are observed ahead of the heat source. The peak temperature from the Figure 4 is observed as 3178K when the heat source reaches the middle of the plate causing melting of the melting the material and forms fusion zone.

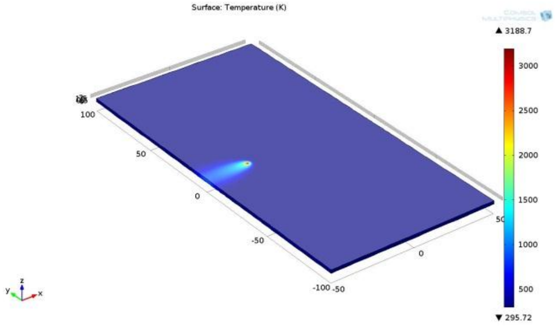


Figure 5. Temperature distribution at time = 5 Sec

Immediate vicinity of the fusion zone is observed with high temperature and forms Heat affected zone. The heat affected zone for the Ti-6Al-4V is found as 1878K from the literatures and same is set as HAZ temperature. Figure 7 shows the position of heat source at the end of the plate and the temperature is observed to be 3930 K since the normal area is very less because of which the temperature gradient is high.

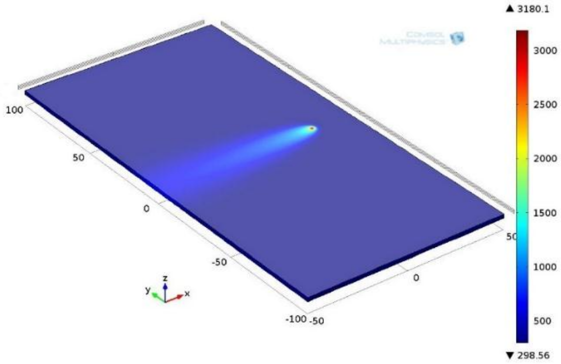


Figure 6. Temperature distribution at time = 15 Sec

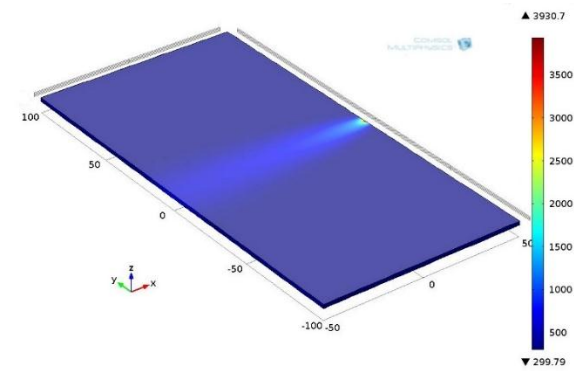


Figure 7. Temperature distribution at time = 20 Sec

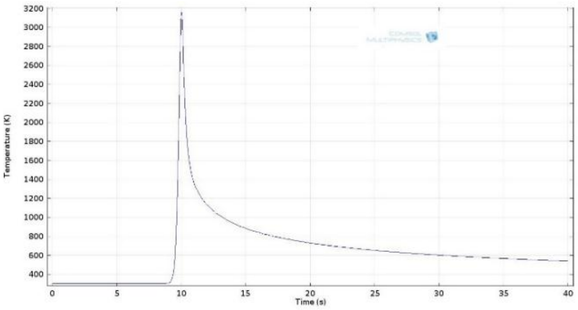


Figure 8. Temperature vs. Time

Figure 8 shows the temp vs. time curve when the heat source approaches at center of plate. As heat source comes near to the center of the plate say t=9 sec the temperature starts rising and attains maximum temperature at t=10 sec i.e. center of plate. As time increases the temperature at the center of the plate starts decreasing.

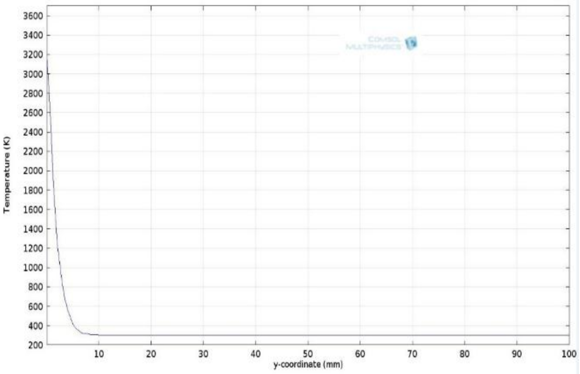


Figure 9. Temperature distribution along transverse direction

Figure 9 shows the temperature distribution of plasma arc on the work piece from the weld centerline which shows that the plasma arc follows the Gaussian distribution. The peak temperature is seen at the weld centerline and along the transverse direction the temperature is getting reduced and attains ambient temperature at a distance of 7 mm.The half width of the molten pool is observed as 2.5mm.

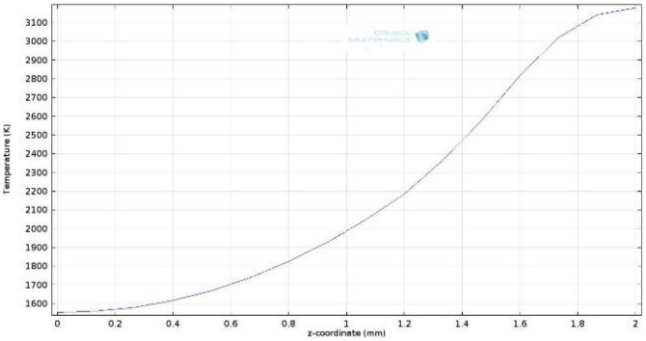


Figure 10. Temperature distribution along thickness of the plate

Figure 10 shows the temperature gradient along the thickness direction. The temperature at the top of the plate is observed as 3178K and the temperature at the bottom surface is 1550K.The melting temperature of the Ti-6AL-4V is 1963K. Upto 1.05 mm distance from the top of the plate is only maintained above 1963K and forms molten pool. Below 1.05 mm from the top of the plate is only heated because of the lack of heat input. Hence partial penetration is obtained and the depth of penetration is observed as 1.05mm.

6. Conclusions

A single bead on plate using plasma arc welding on 2 mm thick Ti-6AL-4V plate has been presented in this paper. A Modified Three Dimensional Conical Heat source and newly developed heat source model were used for performing the simulation to predict the weld bead geometry and temperature distribution using COMOSL Finite Element code. The simulated macrograph was compared with the macrograph obtained from the experiment. Based on the investigation, it is inferred that the predicted weld bead geometry using newly developed three dimensional heat source model is observed to be in good agreement with the experiment result.

7. References

1. Rodney Boyer, Gerhard Welsch and E.W.Coolings, Material Properties handbook: Titanium Alloys, ASM International, 2007

2. C.S.Wu, H.G.Wang and Y.M.Zhang. A New Heat Source Model for Keyhole Plasma Arc Welding in FEM Analysis of the Temperature Profile, Welding Journal, 284-291-S (December 2006)

3. Aditya A Deshpande, Andrew B Short,Wei Sun, D Graham McCartney, Lei Xu and Thomas H Hyde, Finite element-based analysis of experimentally identified parametric envelopes for stable keyhole plasma arc welding of a titanium alloy, The Journal of Strain Analysis for Engineering Design, vol. 47 no. 5 266-275, (July2012)

4. A. Short, D.G. McCartney, P. Webb and E. Preston, Parametric Envelopes for Keyhole Plasma Arc Welding of a Titanium Alloy,ASM International, Trends in Welding Research, Proceedings of the 8th International Conference,P-690-696

5. Mahdi Jamshidinia, Fanrong Kong and Radovan Kovacevic, Numerical Modeling of Heat distribution in the electron beam welding of Ti-6Al-4V, Journal of Manufacturing Science and Engineering, Vol. 135/ 061010-1, December 2013

6. R.Goyal E.Johnson et.al. A Model convection equation for the convection coefficient for Thermal analysis of welded structures, Trends in Welding Research: Proceedings of the 8th International, ASM international, Volume 1.321-327

7. Matthew J.Donachie, Titanium A Technical Guide, ASM International, Second Edition