Numerical modeling of Flux assisted Gas Tungsten Arc Welding (F-GTAW) process of Duplex Stainless Steel (DSS)

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Abstract. A three dimensional transient Finite Element Model (FEM) of Flux assisted Gas Tungsten Arc Welding (F-GTAW) to predict the temperature cycle at the weld line of Duplex Stainless Steel (DSS2205) is proposed in this study using gaussian moving source. The proposed finite element model is validated using the experimental results published in the literature. The temperature history plot obtained from the FEM is compared with the experimental data. The results show that the peak temperature value at a surface node of the FEM is matching with the maximum temperature obtained at the surface of the weld. The proposed model has the capability to predict the temperature history of the entire welding cycle. The temperature distribution profile obtained from the FEM of F-GTAW is also compared with the conventional GTAW model. The proposed FEM model has been developed using Ansys software.

1. Introduction
Gas Tungsten arc (GTA) welding is one of the most popular welding process for joining stainless steel materials and as well as non-ferrous materials. Tungsten electrode is used in this process for producing arc. During welding, the weld zone is protected from the oxidation and other atmospheric contaminations using shielding gases such as argon or helium. A constant current power source is used in GMAW process to produce the arc to melt the joining materials. GTAW resulting in high quality stronger welds and provides better control for the operators compared with Gas Metal Arc Welding (GMAW) and Shielded Metal Arc Welding (SMAW) process. GTAW can be welded in all positions and no slag is produced during the process. Thermal distortions are also minimum in GTAW. The popularity of GTAW is due to its ability to weld wide variety of materials such as mild steel, stainless steel, titanium alloys, aluminum alloys, and copper alloys [1].

GTAW process has a number of advantages over other conventional welding processes such as a) welding wide variety of materials b) no formation of spatter or slag, spark, smoke and c) allows for welding all positions. The important limitation of the process includes a) requirement of high level of operator skill b) higher level of UV radiation c) requirement of good eye and hand coordination and d) limitation in producing a higher depth of penetration weld in single pass. Among these limitations, GTAW is less popular in certain industrial applications due to the lesser depth of penetration achieved in single pass. This will lead to more numbers of passes to complete the weldment and as well as increase in completion time of the weldment.

Duplex stainless steels contains both ferrite and austenite in its micro-structure. Duplex stainless steel is a two phase alloy has equal composition of ferrite and austenite phases. Duplex stainless steels have good mechanical properties and exceptional resistance to stress, pitting and
crevice corrosion cracking. Due to its good weldability, it is being used in fabrication of variety of structural and process equipments such as heat-exchangers, columns, condensers, reactors, pressure vessels, and pipes. These components have applications in industries such as chemical, petrochemical, oil&gas, desalination, nuclear, and solar. In recent years, Flux activated TIG welding of duplex stainless steels have become increasing interest among researchers due to their increasing applications in industries. Only limited studies have been carried out in activated flux TIG welding of duplex stainless steels.

Various attempts were made to improve the depth of penetration during the GTA welding of materials. Off late, use of fluxes in GTAW improved the depth of penetration thereby improved productivity. The process is termed as Flux assisted GTAW (F-GTAW) or Activated flux TIG welding (A-TIG). Mainly the fluxes used for improving the depth of penetration are of oxides, chlorides and fluorides. Few studies have been carried out to improve the depth of penetration using fluxes in GTAW process.

Kuang-Hung Tseng [2] studied the effect of various oxide fluxes during the activated GTAW of 316L stainless steel plates. They have investigated the GTAW process using MnO2, TiO2, MoO3, SiO2 and Al2O3 fluxes. From their studies was found that SiO2 flux increased the weld penetration and Al2O3 flux reduced both weld depth and weld width. Compound fluxes were tried by the researchers for improving the depth of penetration. Venkatesan et al. [3] used multi component fluxes for improving depth of penetration in welding AISI 409 Stainless Steels. They have used the mixture of TiO2 and SiO2. Experiments were conducted using compound fluxes of TiO2, SiO2, Cr2O3 and MoO3 for joining AISI 409 stainless steel using plasma arc welding and TIG welding by Her-Yueh Huang [4]. Hsuan-Liang Lin et al. [5] studied the depth of penetration in TIG welding of Inconel alloy using compound fluxes. It was concluded that mixture of SiO2 and MoO3 resulted in better penetration. Devendranath [6] studied the fusion zone microstructure of the post heat treated flux assisted TIG welded Inconel alloy. The outcome of flux on penetration depth was also studied by them. They have optimized the process parameters for achieving maximum penetration depth using SiO2 and MoO3 compound flux. The mechanical properties were also part of their study. It was found that post heat treated specimen gave a better tensile strength over as-welded specimen. Also, post heat treated specimen showed a better joint efficiency compared to as-welded specimen.

Xu [7] studied on the oxide fluxes in TIG welding and found that reversed Maragoni convection and arc constriction are the factors that increased the depth of penetration. They have studied the TIG welding shape variations for the Nickel based super alloy using Titanium Oxide fluxes. Heat transfer and fluid flow models were developed in their study. Finite element simulations have been carried out by Attarha et al. [8] and predicted the temperature distributions in TIG welding of duplex stainless steels using ‘ABAQUS’ software. Residual stress in TIG welding of carbon steel plates is studied by Dean Deng [9] using‘ABAQUS’software. Temperature distributions in TIG welding of 2205 Duplex stainless steel using adaptive heat source was studied by Daha et al. [10]. Balasubramaniam et al. [11] used Gaussian heat source model for laser welding of SS304 steel. Andrea Capriccioli et al. [12] performed thermal and mechanical simulations for laser and TIG welding process using ‘Ansys’ software. Recently, Finite element model for joining Duplex Stainless Steel (DSS-2205) has been developed by Nanda Naik et al. [13]. A non-linear thermal analysis has been carried out in their study using double-ellipsoidal heat source. Temperature distributions, weld-bead profile and penetration depth were simulated using the SYSWELD software. A Multi component activated flux was used in their study. Fusion zone temperature, depth of penetration, bead width and temperature distribution around the weld line were estimated in their study.

The present work deals with developing a three dimensional transient Finite Element Model (FEM) of Flux assisted Gas Tungsten Arc Welding (F-GTAW) of Duplex Stainless Steel (DSS2205) using ‘Ansys’ software with an objective of predicting the temperature profile in the weld line for the entire welding cycle. A gaussian heat source is utilized in this study. The FEM has been validated by comparing the obtained results with the results published by Nanda Naik [13]. Temperature
The distribution profile of the Flux assisted GTAW model is compared with the temperature distribution profile of the conventional Gas Tungsten Arc Welding model.

2. Heat Source Model

In a welding process, the temperature distribution is governed by the heat conduction equation. The relationship is shown in equation (1).

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

(1)

Where ‘T’ is the temperature, ‘k(T)’ is the thermal conductivity, ‘\( \rho(T) \)’ is the specific mass, ‘\( C_p(T) \)’ is the specific heat, and ‘Qv’ is the volumetric heat flux. The boundary condition on the external surface of the body consists of heat transfer due to convection. The convective heat transfer equation is given in equation (2).

\[
q_c = \rho(T) h_c (T - T_0)
\]

(2)

Where ‘T’ is the temperature of the external surface, ‘\( T_0 \)’ is the temperature of the gas or liquid and ‘hc’ is the coefficient of convective heat transfer. The heat of welding arc is modeled as a travelling heat source with a gaussian distribution. The heat flux distribution is related to the radial position ‘r’ given in equation (3).

\[
q(r) = \frac{\rho U I}{2 \pi r} e^{-\left(\frac{r^2}{\sigma^2}\right)}
\]

(3)

Where \( q(r) \) is the surface flux at radius ‘r’, ‘h’ is the efficiency coefficient, ‘U’ is the voltage, ‘I’ is the current and ‘\( \sigma \)’ is the radial distance from the center \([14]\).

3. Numerical Modeling Using Ansys

A three dimensional transient finite element model of Flux assisted Gas Tungsten Arc Welding (F-GTAW) of Duplex Stainless Steel (DSS2205) material is developed using ‘Ansys’ software. The flux used in this study is SiO2. The temperature versus time plot is generated at a node in the top surface of the weld center. Simulation results are compared with the results available in the literature. A temperature profile of the heat-affected zone is also generated for the F-GTAW process and is compared with the temperature profile generated without the use of the flux. The procedure involved in this work includes a) Material modeling b) Meshing c) Modeling heat source d) Defining boundary condition and e) Simulation and post processing.

3.1. Modelling

A three dimensional model of the weld plate is created with a total dimension of 300mm×125 mm×10mm. The model is created as two separate plates. The flux is modeled as a separate layer above the weld plate with the dimension 300mm×30mm×1mm. The material properties are assigned as per Table 3.1.

| Material | Density (kg/m³) | Specific heat (J/kg°C) | Thermal conductivity (W/m°C) |
|----------|----------------|------------------------|----------------------------|
| DSS2205  | 7860           | 450                    | 19                         |
| SiO2     | 2220           | 745                    | 1.5                        |
| Air      | 1.225          | 1006.4                 | 0.02423                    |

3.2. Meshing

Contact element is provided between the weld plates and between the flux and weld plates. Face split is applied on the flux layer to generate the weld line. A fine mesh is provided at the weld zone and the vicinity of the weld zone. The mesh is generated by designating number of divisions as 80 for edges
along ‘z’ axis, 60 along ‘x’ axis and 4 along ‘y’ axis respectively. In case of flux, the numbers of division are 80 along ‘z’ axis, 40 along ‘x’ axis and 2 along ‘y’ axis. In case of meshing along ‘x’ axis, the source travel path being the area under consideration, the weld area is defined with finer mesh. A 20 node thermal element ‘SOLID90’ is used for modelling. The number of nodes are 1, 72, 350 and the number of elements is 55, 452. Figure 1.1(a) shows the ‘Ansys’ model of the weld plate geometry and flux. Figure 1.1(b) shows the meshed model using ‘SOLID90’ element. The material properties of duplex stainless steel at different temperatures are shown in Table 3.2.

![Image](https://example.com/image.jpg)

(a)  
(b)

Fig.3.1. a) Weld plate geometry and flux (b) Meshing with SOLID90 Element

Table 3.2. Material properties of Duplex stainless steel at different temperatures

| Temperature (K) | Thermal Conductivity (W/mK) | Specific Heat (J/kg K) | Density (Kg/mm³) |
|----------------|------------------------------|------------------------|------------------|
| 293            | 14                           | 470                    | 7.84             |
| 373            | 15                           | 500                    | 7.71             |
| 473            | 17                           | 530                    | 7.78             |
| 573            | 18                           | 560                    | 7.68             |

3.3. Boundary Condition and Heat Source

Heat losses in the form of conduction and convection are applied at the weld surface. The bottom surface is excluded from convection. A moving volumetric Gaussian heat source is applied at the weld joint. An Ansys Application Customization Toolkit (ACT) sub routine using ‘PYTHON’ language is used to apply the three dimensional moving heat source. The heat intensity per unit area is applied to the model as shown in the equation (1). Figure 2 shows the boundary conditions applied to the model.

Heat intensity per unit area, \( Q = \frac{\eta VI}{A} \)  

The welding speed, voltage, ‘V’ and current, ‘I’ used for welding simulation is shown in the Table 3.3. Heat input efficiency, \( \eta \) is taken as 0.85 [13]. The simulation is carried out for a single pass and without the use of any filler material.

TABLE 3.3. GMAW parameters

| Current (A) | Voltage (V) | Weld Speed (mm/s) | Ambient Temperature (°C) |
|------------|-------------|-------------------|--------------------------|
| 100        | 14.5        | 1.5               | 20                       |
4. Results and Discussions
The temperature-time plot of a surface node at weld center is obtained for the F-GTAW ‘Ansys’ model for Duplex Stainless Steel (DSS2205) is shown in Fig 4.1. The plot is compared with the result obtained by Nanda Naik [13]. The peak temperature obtained at surface node at the weld center is 1850°C. The peak temperature matches with the results published in Nanda Naik [5]. This shows the validity of the proposed model. Also, the temperature distribution profile of the F-GTAW for Duplex Stainless Steel (DSS2205) is shown in Figure 4.2.

![Temperature-Time plot of a surface node at weld center for the F-GTAW for Duplex Stainless Steel (DSS2205).](image1)

![Temperature distribution profile of the F-GTAW Ansys model for Duplex Stainless Steel (DSS2205).](image2)

Further, FEM of the TIG welding process has been carried out without the application of the SiO2 flux. From the ‘Ansys’ simulation of the conventional GTAW for Duplex Stainless Steel (DSS2205), the peak temperature obtained at a surface node at weld center is 1100°C. The temperature-time plot is shown in the Figure 4.3. Temperature distribution profile of the conventional GTAW is shown in the Figure 4.4. It is to be noted that because of the application of SiO2 flux there is an increase of 750°C is achieved in the center of the weld line. This increase in temperature will increase the depth of weld penetration as compared to the conventional GTAW process.
5. Conclusion
A three dimensional transient Finite Element Model (FEM) of SiO2 Flux assisted Gas Tungsten Arc Welding (F-GTAW) of Duplex Stainless Steel (DSS2205) is proposed in this study using a gaussian moving heat source. Time – Temperature plots and temperature distribution profiles were obtained for F-GTAW process and conventional GTAW process. The proposed FEM has been validated by comparing the peak temperature obtained at the surface node of the weld line with the results published in the literature. The temperature-time plot obtained from the simulation model is in-line with the experimental results published in the literature. There is an increase of 750°C is noticed during the welding of Duplex Stainless Steel plates with the application of SiO2 flux. The increase in temperature is influencing the increase in depth of penetration. The increase in depth of penetration will lead to weld higher thickness steel sections, which is not possible in the convention GTAW process. The proposed FEM has the capability to predict the temperature history throughout the GTAW process. Further, FEM proposed in this study will be enhanced by modelling with compound fluxes and the results can be validated by conducting experimental studies. GTAW process can also be studied with double ellipsoidal heat source models.

References
[1] R. S. Vidyarth, D. K. Dwivedi, Activating flux tungsten inert gas welding for enhanced weld penetration, Journal of Manufacturing Processes, vol. 22, pp. 211–228, Apr. 2016.
[2] K.-H. Tseng, C.-Y. Hsu, Performance of activated TIG process in austenitic stainless steel welds, Journal of Materials Processing Technology, vol. 211, no. 3, pp. 503–512, Mar. 2011.
[3] G. Venkatesan, J. George, M. Sowmyasri, V. Muthupandi, Effect of Ternary Fluxes on Depth of Penetration in A-TIG Welding of AISI 409 Ferritic Stainless Steel, Procedia Materials Science, vol. 5, pp. 2402–2410, 2014.
[4] H.-Y. Huang, Research on the activating flux gas tungsten arc welding and plasma arc welding for stainless steel, Metals and Materials International, vol. 16, no. 5, pp. 819–825, Oct. 2010.
[5] H.-L. Lin, T.-M. Wu, Effects of Activating Flux on Weld Bead Geometry of Inconel 718 Alloy TIG Welds, *Materials and Manufacturing Processes*, vol. 27, no. 12, pp. 1457–1461, Dec. 2012.

[6] K. D. Ramkumar, R. Ramanand, A. Ameer, K. A. Simon, N. Arivazhagan, Effect of post weld heat treatment on the microstructure and tensile properties of activated flux TIG welds of Inconel X750, *Materials Science and Engineering: A*, vol. 658, pp. 326–338, Mar. 2016.

[7] Y. L. Xu, Z. B. Dong, Y. H. Wei, C. L. Yang, Marangoni convection and weld shape variation in A-TIG welding process, *Theoretical and Applied Fracture Mechanics*, vol. 48, no. 2, pp. 178–186, Oct. 2007.

[8] M. J. Attarha, I. Sattari-Far, Study on welding temperature distribution in thin welded plates through experimental measurements and finite element simulation, *Journal of Materials Processing Technology*, vol. 211, no. 4, pp. 688–694, Apr. 2011.

[9] D. Deng, FEM prediction of welding residual stress and distortion in carbon steel considering phase transformation effects, *Materials & Design*, vol. 30, no. 2, pp. 359–366, Feb. 2009.

[10] B. Šimek, I. Kovaríková, K. Ulrich, Microstructure and Properties of Plasma Arc Welding with Depth Penetration Keyhole SAF 2205 Duplex Stainless Steel, *Advanced Materials Research*, vol. 664, pp. 578–583, Feb. 2013.

[11] K. R. Balasubramanian, T. Suthakar, K. Sankaranarayanasamy, G. Buvanashekar, Finite Element analysis of heat distribution in laser beam welding of AISI 304 Stainless Steel sheet, *International Journal of Manufacturing Research*, vol. 7, no. 1, p. 42, 2012.

[12] A. Capriccioli, P. Frosi, Multipurpose ANSYS FE procedure for welding processes simulation, *Fusion Engineering and Design*, vol. 84, no. 2–6, pp. 546–553, Jun. 2009.

[13] K. N. Naik, K. R. Balasubramanian, M. Vasudevan, Finite Element Simulation of A-TIG Welding of Duplex Stainless Steel 2205 Using SYSWELD, *Applied Mechanics and Materials*, vol. 592–594, pp. 374–379, Jul. 2014.

[14] L. Karlsson, J. Goldak, Computational Welding Mechanics, *Encyclopedia of Thermal Stresses*, pp. 630–637, 2014.