Monitoring TIG welding using infrared thermography – simulations and experiments

Abstract. In the current work a 3D model has been developed to predict the thermal cycles during the Tungsten Inert Gas welding of Aluminum 2219. This paper describes the step by step procedure adopted to get the actual cooling rate during the TIG welding process both experimentally and numerically. The model was developed in the COMSOL Finite Element Package and considered a Gaussian heat distribution. The developed model then validated using the experimental data collected in field experiments on actual large propellant tanks. Temperature measurements were performed using infrared Camera. Results show a close comparison between model and experiment.

Słowa kluczowe: *Infrared Thermography, Online Monitoring, Finite Element Method, Image Analysis.*

Introduction

Fusion welding is a joining process that involves the phase change of materials. These processes are widely used in many engineering applications such as aerospace, automotive and ship building industries. A good quality weld is characterized by material composition, joint condition, relative position of the welding arc to the joint and welding parameters such as arc current, arc voltage and torch travel speed. Therefore choosing an appropriate set of welding parameters becomes one of the most important tasks in TIG welding process. In the current industrial practice welding processes are developed largely based on trial and error experiments incorporating with engineer’s knowledge and experience of previous similar designs. So it is very important to identify and optimize various welding parameters and thereby control the process for the defect free manufacturing [1].

Arc welding is inherently a thermal processing method. To this end, infrared sensing is a natural choice for weld process monitoring. Infrared sensing is the non contact measurement of emissions in the infrared portion of the electromagnetic spectrum. Many investigators have used thermographic system for the measurement of temperature distribution and control of welding online [2–6]. Most of these measurements are reported from the weld pool region. In the current study we explored the monitoring of solidified weld region just after the weld torch passes. This online measurement technique is well utilized for the defect identification during welding process [7].

The various transport phenomena in the weld pool directly affect the size and shape of the weld formed, solidification microstructure, the formation of the weld defects such as porosity and humping, and the temperature distribution in the fusion zone and heat affected zone. Simulation tools based on finite element method are very useful in the prediction of temperature fields in welding. Owing to the growing needs of automation and better weld quality control there have been several attempts to model the actual welding phenomena by considering all the physics involved in the weld pool [8–14]. All these models require the specification of net thermal input from the welding arc to the work piece along with its spatial distribution. The research on welding heat source models dates back 1940s and Rosenthal first proposed a mathematical model of the moving heat source under the assumptions quasi-stationary state and concentrated point heating in the 3D analysis [15]. In the late 1960s, Pavelec et al. suggested a circular disc heat source model with Gaussian distribution of heat flux on the surface of work piece. Goldak et al. further developed a double ellipsoidal power density distribution of heat source model below the welding arc, which can accurately simulate different type of welding processes with shallow and deep penetration [16]. These heat source models and some simplified models have been widely used in welding simulation for prediction of temperature field, distortion and the residual stresses.

In the current study to simulate the heat flux from the arc we used the Gaussian heat distribution because of the consideration that less heat flux penetration is involved in arc welding process than the high power density welding processes (EBW and LBW), where the double ellipsoidal model can capture the flux penetration effectively.

Modeling and Simulations

Mathematical and Numerical Model

Both 2D and 3D heat conduction models were developed to simulate the TIG welding process. The developed models consider a moving heat source along the Aluminum plate. The thickness of the plate is given in the thickness axis and is positive toward the upper side. The weld path is defined at the center as a separate surface.

The heat source will move over this surface along the positive x direction with a constant velocity v. As a result of the heat input a molten pool will create under the heat source. In the current study we assume that the material is homogeneous and thermo physical properties are constant also the formation of molten pool and the forces acting in the weld pool are not considered. The details of our 2D modeling part is published earlier and is available online [17]. For a three-dimensional unsteady state heat transfer in the isotropic welding plate without any heat generation, the governing equation can be expressed as follows:

\[
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) = \rho c \frac{\partial T}{\partial t}
\]
Where \( T \) determines the temperature of the plate, \( k \) is the thermal conductivity, \( \rho \) is the density of the plate, \( c \) is the specific heat and \( t \) represent the time duration. The convective and radiative boundary heat losses were considered and it is represented as follows:

\[
n_t (kVT) = Q + h(T_{\text{amb}} - T) + C_{\text{conv}} (T_{\text{amb}}^4 - T^4)
\]

(2)

Where \( Q \) is the inward heat input from the electric arc, \( h \) is the convective heat transfer coefficient, \( n \) is the vector normal to the surface. The welding arc heat source is considered as a distributed boundary heat source. The weld path is defined as a boundary in the geometry and the heat source term is expressed as a boundary expression in the model. The Gaussian heat source model is defined as follows:

\[
Q = \frac{3\eta VI}{\pi r_b^2} \left( e^{-\frac{1}{3} \left( \left( \frac{x - x_0}{r_b} \right)^2 + \left( \frac{y - y_0}{r_b} \right)^2 \right)}\right)
\]

(3)

Where \( \eta \) is the arc efficiency, \( V \) and \( I \) are voltage and current values, \( r_b \) represents the Gaussian base radius and \( x_0 \) and \( y_0 \) are coordinate points to locate and define the motion of the weld torch along the weld path. The coordinate point \( y_0 \) is given by \( v \times t \), where \( v \) is the velocity of the weld torch and \( t \) is the welding time. The initial condition is assumed as ambient temperature 300K.
focused to an area 150 mm away from the weld torch as shown in Fig. 5. The length along the weld the camera sees was about 100 mm. This measurement system is adopted after several feasibility studies in order to avoid the saturation of detector due to the high temperature infrared emissions near the weld pool region.

The thermal image obtained during the experiment is shown in Fig. 6. The infrared camera obtains thermal maps called thermographs from the distribution and a custom built interface transfers these images from the camera to the computer for further analysis. The thermal image obtained during the welding process at a certain tank location.

Fig. 6. Schematic of experimental set up showing the field of view of the measurement

Due to the tilted camera the finger clamps used for the fixture is also present in the thermal image. Steel is used as finger clamps. From the thermal image it is observed that the finger clamps were at a high temperature compared to the AA 2219 weld region. The reason is the FOV is away from the weld torch and because of that the aluminum gets cool fast and the steel get heated up. Due to the low thermal conductivity of steel it is showing a high temperature compared to aluminum.

Image analyzing algorithms were developed to find the transient temperature decay data from the raw thermal images in which the material is moving. A more detailed account of the procedure is highlighted in Fig. [7]. The cooling rate of a point at the center of the weld bead is measured using the algorithm and the measurements were taken at different locations of the welded cylinder. The material is moving through the field of view. Each pixel area on the material stays only for 12 seconds in the field of view. This was found out using the tracking of points from the experimental data at different locations. The algorithm has taken care of the welding speed, frame rate at which the thermal images were taken and the horizontal pixel position. The point plot in Fig. 7 corresponds to the cooling rate at different locations and the dotted line is the average value of the measured experimental data.

Fig. 7. Flow diagram details of the time-temperature profile generation

**Results and Conclusion**

Fig. 8. Comparison of cooling curves for experiment and simulation

A numerical model of the TIG welding process to perform simulation of the surface thermograms is developed using the finite element method and implemented it using the commercial software COMSOL Multiphysics. The validation of the 2D and 3D models were carried out using the experimental data collected in field experiments on actual large propellant tanks. The simplified 2D model developed initially, with a heat source that was optimized using the experiment, gave a close comparison with the experimental data in the entire non-defective region. The development of the 3D simulation model for the non defective weld case with the Gaussian heat source parameters gives a close comparison with the experiment. The spread of experimental data in the non defective region is verified by the variation of weld process parameters. The parametric study shows that the Gaussian heat source radius is less sensitive to the temperature variation in the observed region but the efficiency values are considerably sensitive to the temperature changes. It is well known from the earlier studies that the heat flow which is away from the
heat source is only affected by the total amount of energy deposited on the material, which is controlled by the efficiency value and the distribution is not important in determining the temperature distribution away from the source as observed for Gaussian base radius.

**Acknowledgment:** This work was financially supported by Indian Space Research Organization, India, under the project entitled Development of an Online Weld Defect Characterization using Thermal Imaging Techniques.

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