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Numerical and experimental studies to characterize the weld width variation for Copper in Gas Tungsten Arc Welding process

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***Abstract*—Weld width variation across the longitudinal direction is a major concern for copper due to its high thermal diffusivity. The study focuses on the weld width characterization across the length of the workpiece using both numerical and experimental studies. The distribution of temperature and heat-affected zone for conduction mode gas tungsten arc welding (GTAW) is studied using numerical calculations of the double ellipsoidal moving heat source model. The analysis of the weld pool geometry and temperature field distribution using a semi-analytical solution for a double-ellipsoidal moving heat source is presented. The influencing welding parameters are the heat energy input and the torch scan velocity as well as the heat source parameters that are heat source dimension, form factor, base material property, and arc efficiency. The experiment is performed on ETP copper of dimension 100mm x 25mm x 15mm. The numerical results are compared with the experimental data of a double ellipsoidal moving heat source, which is in decent agreement.**

***Keywords-component*—welding; numerical modelling; experimental characterization; moving heat source; GTAW**

I. INTRODUCTION

Welding is a widely employed technique for permanently joining two similar or dissimilar metals, resulting in a robust and durable connection. Various welding processes such as Gas Tungsten Arc Welding (GTAW), Submerged Arc Welding (SAW), and Gas Metal Arc Welding (GMAW) are commonly used across industrial and construction applications. During welding, fluid flow occurs within the molten metal, significantly influencing the thermal history, cooling rate of the fusion zone, and the characteristics of the heat-affected zone (HAZ). These thermal dynamics, particularly the heat input and cooling rates, play a crucial role in determining the final mechanical properties of the welded joint [1]. Consequently, the control of torch travel speed and heat input parameters is essential for achieving desired weld quality. Both computational and theoretical scaling approaches have been developed to study these complex phenomena [2], with the Finite Element Method (FEM) being recognized as one of the most effective tools for numerical analysis in this context [3].

Modeling the welding process typically involves a coupled analysis of thermal, mechanical, and metallurgical aspects. The modeling often begins with thermal analysis to determine the temperature distribution within the workpiece. The heat source is modeled as a moving and spatially distributed function, enabling the prediction of the HAZ and weld pool geometry. Pioneering models of moving heat sources were introduced by Rosenthal [4] and further refined by Goldak et al. [5], who proposed a three-dimensional, double ellipsoidal moving heat source. Nguyen et al. [6] developed an analytical solution for transient temperature fields in a semi-infinite medium subjected to a moving heat source using Green's function. Their model demonstrated the capability to predict weld pool geometry effectively. Building upon Goldak's double ellipsoidal model, Goyal [7] conducted analytical investigations into the thermal behavior and weld pool geometry in pulsed current GMAW. The dimensions of the heat source in the double ellipsoidal model are functions of key welding parameters, including heat input and torch travel speed. By varying these parameters, the temperature distribution and weld pool geometry can be controlled. However, one of the limitations of this approach is the need for iterative adjustment of multiple parameters to achieve a suitable thermal profile, making the process somewhat trial-and-error based [8].

Despite numerous advancements in mathematical modeling of welding processes, the inherently non-linear and complex nature of the phenomena continues to pose significant challenges.

The present study aims to predict the temperature field

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and weld pool geometry using the double ellipsoidal heat source model under varying heat fluxes and torch travel speeds. The temperature distribution is obtained using the analytical solution proposed by Nguyen et al., and the resulting thermal profiles and weld geometries are analyzed. Experimental validation is also conducted, demonstrating good agreement with the predicted peak temperatures in the weld pool.

II. Analytical Form of Double Ellipsoidal Moving Heat Source

Rosenthal [4] provided one of the earliest analytical solutions for heat distribution in arc welding by modeling the heat input as a point source. His approach incorporated moving coordinate systems and solved the Fourier partial differential equation of heat conduction, enabling the analysis of various welding problems. However, the solution was derived under the assumption of quasi-steady-state conditions, which are valid only at locations sufficiently distant from the heat source.

To improve upon this, a volumetric heat source model was introduced, wherein the heat input was distributed over a semi-ellipsoidal volume using a Gaussian heat flux distribution. While this model improved the representation of the thermal field, discrepancies were noted between the simulated and experimental temperature gradients. Specifically, the temperature gradients ahead of the arc were steeper in experimental observations than those predicted by the model, whereas the gradients behind the arc were less steep than observed.

To address these inconsistencies, the concept of a double ellipsoidal heat source was proposed, as illustrated in Fig. 1. This model combines two semi-ellipsoidal heat sources—one positioned in front of the arc and the other behind it—allowing for a more accurate simulation of the asymmetrical temperature field observed in actual welding processes. Subsequently, a generalized analytical solution was developed based on this model, demonstrating improved accuracy in predicting transient temperature distributions and weld pool geometries.

For origin as a point heat source, Rosenthal equation for temperature distribution in a semi-infinite plate with thickness h, in a cartesian coordinate x,y and z is expressed as

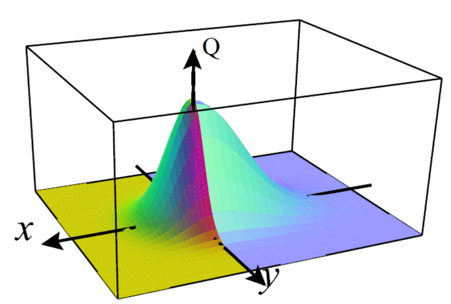

Figure. 1. Heat flux distribution of a double ellipsoidal heat source

$$dT = \frac{1}{4}\frac{6\sqrt{3}Qdt'}{\rho c\alpha b\pi\sqrt{\pi}[4\pi\alpha(t-t')]^{3/2}} \tag{1}$$

$$T - T_0 = \frac{Q_p}{2\pi k}e^{-\alpha v\xi}\left[\frac{e^{-\alpha vM}}{M} + \sum_{n=1}^{n=\infty}\left(\frac{e^{-\alpha vM_n}}{M_n} + \frac{e^{-\alpha vM_n^{'}}}{M_n^{'}}\right)\right] \tag{2}$$

where M is the distance from the central axis, T_0 is the initial temperature of the material on which welding operation is performed, k is the thermal conductivity of the material, α is thermal diffusivity of base metal, v is welding speed, and ξ is the distance of a point from the central axis.

$$\xi = x - vt \tag{3}$$

For M, M_n and $M_n^{'}$

$$M = \sqrt{\xi^2 + y^2 + z^2} \tag{4}$$

$$M_n = \sqrt{(2nd - z)^2 + \xi^2 + y^2} \tag{5}$$

$$M_n^{'} = \sqrt{(2nd + z)^2 + \xi^2 + y^2} \tag{6}$$

The analytical solution for the transient temperature field of the semi-infinite body for any point (x,y,z) is proposed by Nguyen.

$$T - T_0 = \frac{3\sqrt{3}Q_d}{\rho c\pi\sqrt{\pi}}\int_0^t\left[\frac{dt^{'}}{\sqrt{(12\alpha(t-t^{'})+a^2)}\sqrt{(12\alpha(t-t^{'})+b^2)}} \times\left(\frac{A^{'}}{\sqrt{(12\alpha(t-t^{'})+c_f^2)}} + \frac{B^{'}}{\sqrt{(12\alpha(t-t^{'})+c_b^2)}}\right)\right] \tag{7}$$

where Q_d is distributed heat input, ρ is density of base metal, c is specific heat, α is thermal diffusivity, a, b, c_f and c_b are double ellipsoidal heat source parameters.

$$A^{'} = r_f exp\left(-\frac{3(x-vt^{'})^2}{12\alpha(t-t^{'})+c_f^2} - \frac{3y^2}{12\alpha(t-t^{'})+a^2} - \frac{3z^2}{12\alpha(t-t^{'})+b^2}\right) \tag{8}$$

$$B^{'} = r_b exp\left(-\frac{3(x-vt^{'})^2}{12\alpha(t-t^{'})+c_b^2} - \frac{3y^2}{12\alpha(t-t^{'})+a^2} - \frac{3z^2}{12\alpha(t-t^{'})+b^2}\right) \tag{9}$$

$$r_f = \frac{2c_f}{(c_f + c_b)} \tag{10}$$

$$r_b = \frac{2c_b}{(c_f + c_b)} \tag{11}$$

The analytical solution of the double ellipsoidal heat source is dependent on parameters such as a, b, c_f, c_b and also on the arc efficiency η_a. The thermophysical properties used are shown in Table 1. From Table 1, the calculations of the

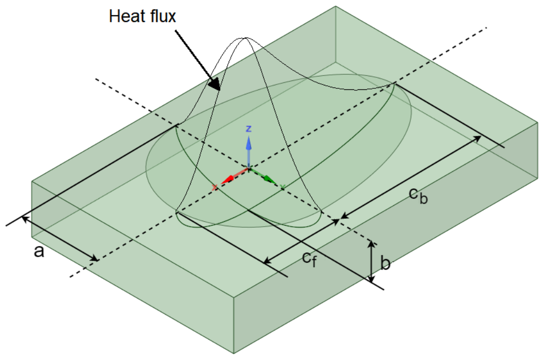

Figure. 2. Double Ellipsoidal moving heat source

analytical equations can arrive at the results shown in Fig.

The validation of the program is done by comparing the results obtained by the Nguyen numerically and experimentally. It shows a good inclination towards the experimental results as shown in Fig. 3.

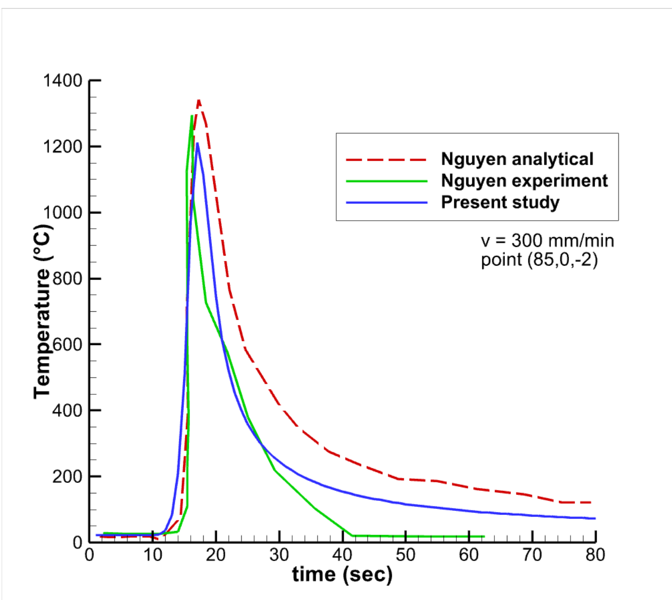

Figure. 3. Present analysis solutions comparison of temperature profile change with time for a point (85,0,2), with the Nguyen numerical and experimental study

III. Experimental setup

The experiment was performed with the purpose to validate the analytical solution which is used to predict the weld pool geometry and temperature field distribution varying different operating parameters. A single scan operation is performed on an electrolytic-touch-pitch copper (ETP-Cu) having parameters mentioned in Table 1. The specimen is shown in Fig. 4. consist of 100mm x 50mm x 15mm dimension. The surface of the workpiece is made smooth with the help of sandpaper. A single-pass weld scan was performed on the ETP-copper under two types of conditions i.e., 1) preheated and 2) without preheating the workpiece.

TABLE. I
Thermo-physical data and parameters used for the study

Thermal data	***Units***
Density	8900 kg m^{-3}
Specific heat	387 J kg$^{-1}K^{-1}$
Thermal conductivity	385 W $m^{-1}C^{-1}$
Thermal diffusivity	1.117×10^{-4} m^2 s^{-1}
Calculation parameters	
Arc efficiency	0.80
Voltage	16 V
Current	230 A

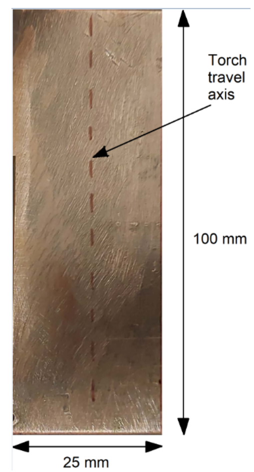

Figure. 4. ETP-Cu marking of torch travel

Fig. 5 & 6 shows the single-pass scan of weld torch over the workpiece without preheating and with preheating condition,, respectively. It can be seen that both the condition leads to different temperature distribution and therefore the heat distribution over the workpiece can be different which is proved analytically. The formation of the heat distribution over the length of the workpiece on the free surface is also calculated analytically and compared with the experimentally obtained profile of the heat distribution shown in Fig. 5.

Figure. 5. Low power single scan on ETP copper without preheating

IV. Result

This study involves a numerical approach to solving the analytical equations (7), (8), and (9) that describe the temperature distribution generated by the double ellipsoidal heat

Figure. 6. Low power single scan on ETP copper with preheating

source model. To carry out these calculations, a computational program was developed using FORTRAN 90. The program evaluates the integrals required to determine the transient temperature field and the geometry of the resulting weld pool.

Figure 7 presents a comparison of temperature profiles at a specific location on the base metal—coordinates (40, 10, 0)—which corresponds to ETP (Electrolytic Tough Pitch) copper. These profiles show how the temperature at this point evolves over time during the welding process. Two conditions were examined: one without preheating the base metal and another with preheating. The analytical model shows good agreement with the observed experimental results.

As the welding torch moves along the x-direction of the workpiece, the temperature at the observation point rises until it reaches a peak, after which it begins to cool. However, the experimentally observed cooling rate is slower than predicted by the model. This discrepancy may be attributed to several factors, including temperature-dependent changes in material properties, variations in the heat transfer coefficient with the environment, and the geometry of the base metal.

Figure 8 illustrates the top view of the weld pool width and its comparison with corresponding experimental data, further validating the model.

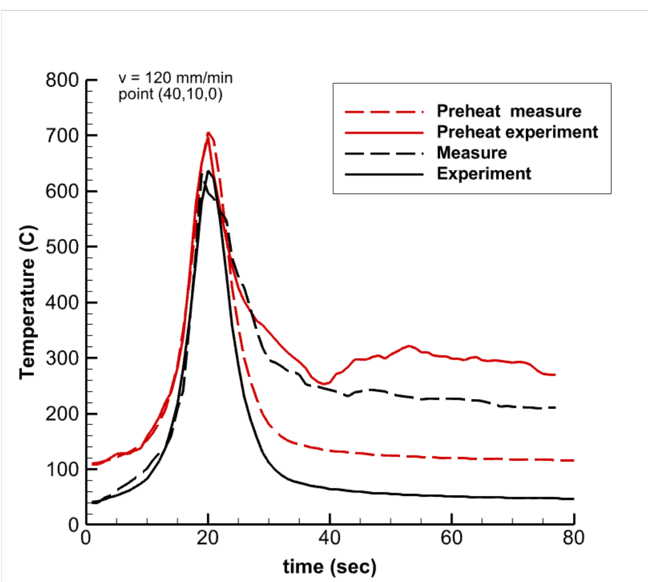

Figure. 7. The plot of temperature profile change with respect to time at a point (40,10,0) when then torch single scan passes over base metal with and without preheating.

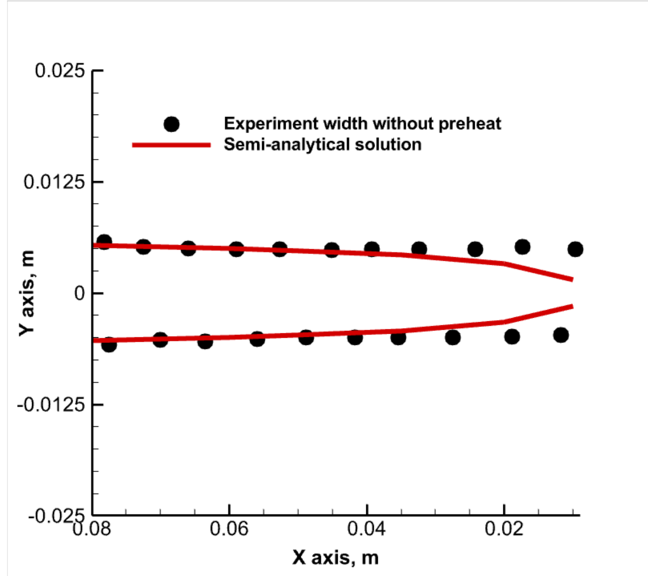

Figure. 8. Single scan in x axis over ETP-Cu at distance 40 mm distance shows the width of the scan comparison with analytical solution.

V. Conclusion

In the present study, the solution of the analytical equations proposed by Nguyen are used to predict the melt pool dimension and temperature field distribution on the base metal.

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