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Research Article

Modeling of Thermel Transport for GMAW

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Investigation of temperature distribution of submerged arc welded plates is essential while designing submerged arc welding joint because the key parameter for the change of weld bead geometry dimension, thermal stress, residual stress, tensile stress, hardness, and so forth is heat input, and heat input is the function of temperature distribution of GMAW process. An attempt is made in this paper to find out the exact solution of the thermal field induced in a semi-infinite body by a moving heat source with Gaussian distribution by selecting appropriate inside volume for submerged arc welding process. It has been revealed that for GMAW, best suitable heat source shape is a combination of semispherical and semioval.

1. Introduction

An attempt of development of mathematical model of travelling heat source was made more than fifty years ago. After that, lots of research work has been continuing on this area. Initially two-dimension surface Gaussian heat source with effective arc radius was adopted to find out temperature distribution on welded plates and weld pool geometry (Eager and Tsai, [1]).

Nguyen et al. [2] presented an analytical solution of transient temperature distribution of a semi-infinite body subjected to three dimensional heat density of semiellipsoidal and double ellipsoidal mobile heat source. Very good agreement between predicted and measured temperature distribution data achieved assuming double ellipsoidal heat source. But there are still some limitations of this analytical solution, that is, this solution is valid only for identical radii and heat dissipation of rear and front ellipsoid. Fachinotti et al. [3] proposed a semianalytical solution which was able to overcome the aforesaid limitations. Nguyen et al. [4] again described an approximate analytical solution for double ellipsoidal heat source in finite thick plates. Their approximate solution can be directly used for the simulation of the welding of finite thick plates without the need for applying the mirror method as required in a semi-infinite body. It is an effective tool for finding thermal stress and microstructure modeling.

Sabapathy et al. [5, 6] and Klobčar et al. [7] attempted to find out thermal field on welded plates for MMA welding process considering flatter and more evenly distributed heat than Gaussian and found excellent comparison with the measured data.

Ghosh et al. [8] investigated heat source shape for submerged arc welding process, but their investigation till near about 10% error in prediction of transient temperature distribution was found.

In this analysis, an attempt is made in this paper to find out the approximate analytical solution of the thermal field induced in a semi infinite body by a moving heat source with Gaussian heat distribution by selecting inside volume of combined spherical and oval shape for GMAW process.

2. Experimentation

Heat energy is lost mainly through conduction along the base metal. During this process, the areas adjoining the weld metal are heated to fairly high temperature. The temperature at different points in the base is taken by infrared thermometers.

2.1. Equipment Used

GMAW unit, mild steel plates size $22 \times 95 \times 300$ mm, Omega scope OS524E, temperature range 2482 °C, accuracy is ±1% rdg or 2 °C whichever is greater, resolution 1°C, response time is 10 ms.

2.2. Experimental Results

Thermal history of GM welded plates is described in Table 1.

3. Thermal Modeling

3.1. Assumption Made in Thermal Model

In developing the thermal model, an attempt has been made to accommodate the actual welding conditions as far as possible. However, the following have been assumed in the thermal model of the welding process.

(i) Density remained constant and did not change with temperature change.

(ii) All other thermal properties were considered as a function of temperature.

(iii) Convective heat lost through all surfaces of the welded plates.

(iv) Heat loss due to radiation.

3.2. Heat Source Model

3.2.1. Gaussian Heat Distribution

Let us consider a combination of semispherical and semi oval heat source in which heat is distributed in a Gaussian manner throughout the heat source's volume. The heat density

Table 1: Temperature readings (taken at the intervals of 10 sec up to 160 sec).

Time (sec)	Temperature (at 1,1,0) on welded plates	Temperature (at 1,1.5,0) on welded plates	Temperature (at 1,2.5,0) on welded plates	Temperature (at 1,5,0) on welded plates
10	30	30	30	30
20	230	183	97	30
30	260	190	100	30
40	275	303	115	30
50	291	235	121	43
60	310	240	129	54
70	330	250	140	53
80	320	254	145	55
90	313	247	151	58
100	289	242	155	58
110	270	235	147	60
120	250	230	140	63
130	235	215	135	63
140	225	202	128	65
150	217	197	123	65
160	205	187	116	68

$q(x, y, z)$ at a point (x, y, z) within semi-spherical and semi oval shape is given by the following equation:

$$\begin{aligned} q(x,y,z) &= q(0)e^{-s(x^2+y^2+z^2)}, \\ q(x,y,z) &= q'(0)\ e^{-(ox^2+(uy^2+wz^2)(e^{mx}))}, \end{aligned} \tag{3.1}$$

respectively, where $q(0)$ is maximum heat density and s, o, u, w, m are heat source parameters. If total heat input is Q_0, then from Figures 1 and 2, it can be written that

$$\begin{aligned} Q_0 &= \frac{1}{2}\left[\iiint_{-\infty}^{\infty} q(x,y,z)dxdydz\right]_{\text{for spherical heat source}}, \\ Q_0 &= \frac{1}{2}\left[\iiint_{-\infty}^{\infty} q(x,y,z)dx\ dy\ dz\right]_{\text{for oval heat source}}, \\ \text{or}\quad &\left[q(0) = 2\left(\frac{s}{\pi}\right)^{3/2} \times Q_0\right]_{\text{for spherical heat source}}, \\ &\left[q(0) = \frac{2\sqrt{ouw}}{\pi^{3/2}} \times \frac{1}{e^{m^2/4s}} \times Q_0\right]_{\text{for oval heat source}}, \\ \therefore\ q(x,y,z) &= \frac{1}{2}\times 2\ \left(\frac{s}{\pi}\right)^{3/2} \times Q_0 e^{-s(x^2+y^2+z^2)} + \frac{1}{2}\times\frac{2\sqrt{ouw}}{\pi^{3/2}}\times\frac{1}{e^{m^2/4d}} \\ &\quad \times Q_0 e^{-(ox^2+(uy^2+wz^2)(e^{mx}))}. \end{aligned} \tag{3.2}$$

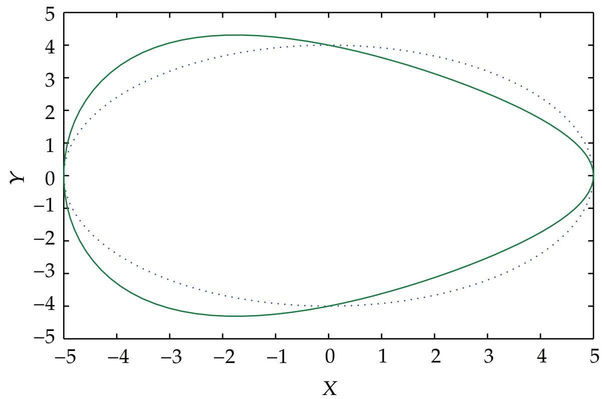

Figure 1: Comparison between ellipsoid (indicated by dotted line) and combination of semi oval and semi spherical heat source shape (indicated by conditions line).

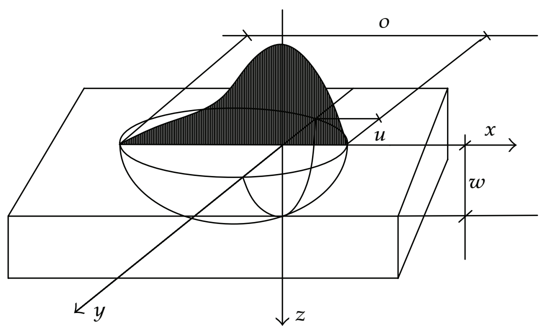

Figure 2: 3D combination of semi oval and semi spherical heat source shape.

As it has been assumed that 50% of total heat input distributed through semi oval shape and remaining 50% through semi spherical shape.

Here,

$$Q_0 = I \times V \times \eta, \tag{3.3}$$

where V, I, η = welding voltage, current, and arc efficiency, respectively.

Arc efficiency is taken 0.9 for GMAW:

$$\begin{aligned} \therefore \quad q(x,y,z) &= \left(\frac{s}{\pi}\right)^{3/2} \times Q_0 e^{-s(x^2+y^2+z^2)} + \frac{\sqrt{ouw}}{\pi^{3/2}} \\ &\quad \times \frac{1}{e^{m^2/4d}} \times Q_0 e^{-(ox^2+(uy^2+wz^2)(e^{mx}))}. \end{aligned} \tag{3.4}$$

4. Analytical Solution

Transient temperature field of heat source in a semi-infinite body is based on solution for the instant point source (dQ) that satisfied the following differential equation of heat conduction of fixed coordinates [2]:

$$dT_{t'} = \frac{dQ\ dt'}{\rho c_p \pi^{3/2} [4\alpha\pi (t - t')]^{3/2}} \times \exp\left(-\frac{(x - x')^2 + (y - y')^2 + (z - z')^2}{4\alpha (t - t')} \right), \tag{4.1}$$

or

$$dT_{t'} = \frac{q(x,y,z) dx\ dy\ dz\ dt'}{\rho c_p \pi^{3/2} [4\alpha\pi (t - t')]^{3/2}} \times \exp\left(-\frac{(x - x')^2 + (y - y')^2 + (z - z')^2}{4\alpha (t - t')} \right). \tag{4.2}$$

If heat is distributed throughout the semi infinite body, then the instant increase of temperature is

$$dT_{t'} = \iiint_{-\infty}^{\infty} \frac{q(x,y,z) dx\ dy\ dz\ dt'}{\rho c_p \pi^{3/2} [4\alpha\pi (t - t')]^{3/2}} \times \exp\left(- \frac{(x - x')^2 + (y - y')^2 + (z - z')^2}{4\alpha (t - t')} \right) dt'. \tag{4.3}$$

So,

$$\begin{aligned} dT_{t'} = {} & \frac{1}{2} \times \left(\frac{s}{\pi} \right)^{3/2} \times \frac{Q_0}{\rho c_p} \times \sqrt{\frac{1}{4a\alpha (t - t') + 1}} \\ & \times e^{-x^2/(4a\alpha(t-t')+1)} \times \sqrt{\frac{1}{4b\alpha (t - t') + 1}} \times e^{-y^2/(4b\alpha(t-t')+1)} \\ & \times \sqrt{\frac{1}{4c\alpha (t - t') + 1}} e^{-z^2/(4c\alpha(t-t')+1)}\ dt' + \frac{1}{2} \\ & \times \frac{Q_0}{\rho c_p \pi^{3/2} [4\alpha\pi (t - t')]^{3/2}} \times \frac{\sqrt{ouw}}{\pi^{3/2}} \times \frac{1}{e^{m^2/4d}} \times I_x \times I_y \times I_z. \end{aligned} \tag{4.4}$$

Here, term 1/2 has been considered as heat source shape is a summation of semi spherical and semi oval.

If heat is distributed throughout the semi infinite body for duration t sec, then an increase of temperature is

$$\int dTt' = \int_0^t \iiint_{-\infty}^{\infty} \frac{q(x,y,z)\,dx\,dy\,dz\,dt'}{\rho c_p \pi^{3/2}[4\alpha\pi(t-t')]^{3/2}} \times \exp\left(-\frac{(x-x')^2 + (y-y')^2 + (z-z')^2}{4\alpha(t-t')}\right)dt', \tag{4.5}$$

where α = thermal diffusivity, cp = specific heat, ρ = mass density, t, t' = time, and dTt' = transient temperature change due to the point heat source dQ at time t', and (x', y', z') = location of instant point heat source dQ at time t'.

When heat source is moving with constant speed v from time $t' = 0$ to $t' = t$, the increase of temperature during this time is equivalent to the sum of all the contributions of the moving heat source during the travelling time as

$$\begin{aligned} T(x, y, z, t) - T_0 = \int_0^t \cdots \frac{1}{2} \times \left(\frac{s}{\pi}\right)^{3/2} \times \frac{Q_0}{\rho c_p} \times \sqrt{\frac{1}{4a\alpha(t-t')+1}} \times e^{-(x-vt')^2/(4a\alpha(t-t')+1)} \\ \times \sqrt{\frac{1}{4b\alpha(t-t')+1}} \times e^{-y^2/(4b\alpha(t-t')+1)} \\ \times \sqrt{\frac{1}{4c\alpha(t-t')+1}}\, e^{-z^2/(4c\alpha(t-t')+1)} dt' \\ + \int_0^t \frac{1}{2} \times \frac{Q_0}{\rho c_p \pi^{3/2}[4\alpha\pi(t-t')]^{3/2}} \times \frac{\sqrt{ouw}}{\pi^{3/2}} \times \frac{1}{e^{m^2/4d}} \times I_{x_1} \times I_y \times I_z\, dt', \end{aligned} \tag{4.6}$$

where, $I_{x_1} = f(x - vt')$, when $I_x = f(x)$.

Here

$$\begin{aligned} I_z &= \int_{-\infty}^{\infty} e^{(-(z-z')^2/(4\alpha(t-t')))} \times \left[e^{-(wz'^2)e^{mx'}}\right] dz' \\ &= \frac{\sqrt{4\pi\alpha(t-t')}}{\sqrt{4w\alpha f(x')(t-t')+1}} \times e^{-(wz^2)/(4wf(x')\alpha(t-t')+1)}, \\ I_y &= \int_{-\infty}^{\infty} e^{(-(y-y')^2/4\alpha(t-t'))} \times \left[e^{-(uy'^2)e^{mx'}}\right] dy' \\ &= \frac{\sqrt{4\pi\alpha(t-t')}}{\sqrt{4u\alpha e^{mx'}(t-t')+1}} \times e^{-(ue^{mx'}y^2)/(4u\alpha(t-t')+1)}, \\ I_x &= \int_{-\infty}^{\infty} e^{(-(x-x')^2/4\alpha(t-t'))} \times \left[e^{-(ox'^2)}\right] \times I_y \times I_z\, dx'. \end{aligned} \tag{4.7}$$

I_x has been calculated by applying numerical method taking appropriate value of integration upper and lower limit.

Table 2: Values of heat source parameters.

Heat source parameters	Values of heat source parameters
o	431250
s	312506
u	312502
w	312508
m	0.2

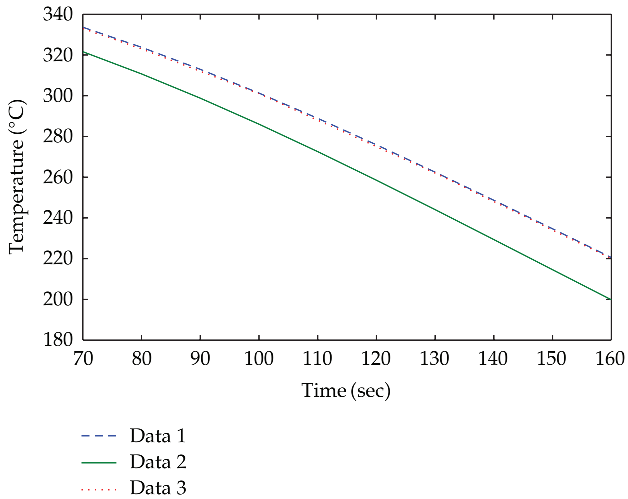

Figure 3: Comparison of measured and calculated thermal history for GMAW.

Where, $T(x, y, z, t)$, T_0 are the temperature at point (x, y, z) any time t, and initial temperature of test specimen, respectively.

4.1. Calculation of Heat Source Parameters

Measured temperature data (Table 1), put in (4.6) and with the help of MATLAB, and values of heat source parameters have been calculated, which are shown in Table 2.

5. Results and Discussion

With the help of (4.6) and measured temperature reading, graph has been plotted and excellent agreement between measured and calculated temperature reading has been found (as shown in Figure 3).

6. Conclusion

This type of numerical investigation is made to estimate two- and three-dimensional transient heat conduction field in semi infinite metallic solid because surface heat transfer strongly affected the temperature distribution in the welded pates. In this study, analytical solutions for the transient temperature field of a semi infinite body subjected to 3D power density moving heat source (such as combined spherical and oval heat source) were found and experimentally validated. Also, it was shown that the analytical solution obtained for combined spherical and oval heat source was a general one that can be applied for any welding process by choosing appropriate values of heat source parameters, and also it can be reduced to 2D Gaussian distributed heat source and classical instant point heat source. Very good agreement between the calculated and measured temperature data indeed shows the creditability of the newly found solution and potential application for various simulation purposes, such as thermal stress, residual stress calculations and microstructure modeling. Previously, in many research works, or heat source shape was assumed double ellipsoidal heat source, but most suitable heat source shape is a combination of semi spherical and semi oval for this particular GMAW machine.

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