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THERMALTRANSPORT PHENOMENON OF SUBMERGED ARC WELDING PROCESS

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Original scientific paper
In present work, thermal transport considering heat radiation by oval heat source shape and heat transfer of molten moving electrode was presented. In present paper, an analytical solution was presented by aggregating temperature increments caused by applying liquid metal and heat radiation of moving electrode. The assumptions for the study were heat source of temperature of applied metal in oval shape and Gaussian distribution of electric heat source. Accuracy of the solution was verified comparing experimental results.

Keywords: *oval heat source, submerged arc welding, thermal transport*

Pojava toplinskog prijelaza kod zavarivanja pod zaštitnim slojem

Izvorni znanstveni članak
U ovom je radu opisan prijelaz topline razmatrajući toplinsko zračenje izvora topline ovalnog oblika i prijenos topline rastaljene pokretne elektrode. Analitičkom se temperaturnom polju približilo ravnim segmentima za ovalni izvor topline s putanjom uzimajući u obzir promjene temperature uzrokovane sljedećim prijelazima (porast temperature zbog izvora topline i rastaljene pokretne elektrode i automatski hlađena područja ranije zagrijana). Točnost rješenja je provjerena usporedbom s eksperimentalnim rezultatima.

Ključne riječi: *ovalni izvor topline, zavarivanje pod zaštitnim slojem, toplinski prijenos*

1 Introduction

In arc welding processes, distributed moving heat sources are generally applied. Due to heating and convective and radiative cooling process in welding processes, temperature field is changed with time and space. Two methods dominate in literature for modeling transient temperature distribution on welded plates. One is numerical solution (finite difference method, finite element method etc.) [11 ÷ 15]. Another is analytical solution [1 ÷ 10], which is described further in present work, where integration transformations are applied.

Nguyen et al. [5] presented analytical solution for the transient temperature field of the semi infinite body subjected to 3-D power density of a dynamic heat source (such as semi-ellipsoidal and double ellipsoidal heat source). However, the results are not satisfactory with the single semi-ellipsoidal 3-D heat source with respect to the double ellipsoidal one.

Fachinotti et al. [6] argued that Nguyen et. al. is only correct when both semi-ellipsoids are equal.

Winczek [21] described an analytical solution for the transient temperature field of half infinite body caused by volumetric heat source with changeable direction of motion. In his work, analytical temperature field was approximated by straight segments for volumetric heat source with trajectory considering temperature changes caused by next transitions (increase in temperature connected to action of heat source and self cooling of areas heated-up earlier).

In present work, transient temperature distribution calculation, considering heat radiation by oval heat source shape and heat transfer of molten moving electrode, were considered.

2 Experimental procedure

The MEMCO semi automatic welding machine with constant voltage, rectifier type power source with a 1200-A capacity was used to join mild steel plates. ESAB SA1 (E8), ∅0,315 cm, copper coated electrode in coil form and ESAB brand, basic fluoride type granular flux was used. The experiments were conducted as per the design matrix randomly to avoid errors due to noise factors. Two pieces of mild steel plates (20 × 30 × 2 cm) were cut and V-groove of angle 60° as per the standards were prepared (as shown in Fig. 1). The 1 mm root opening was selected to join the plates in the flat position keeping electrode positive and perpendicular to the plate. The job was firmly fixed to a base plate and then the submerged arc welding was finally carried out. Experimental results are tabulated in Tab. 1. Temperatures were measured at different points of the welded plates except for welding line which was measured by infrared thermometers (OMEGA SCOPE OS524E, temperature range 2482 °C, accuracy was ±1 % rdg or 2 °C whichever was greater, resolution 1 °C, response time 10 ms).

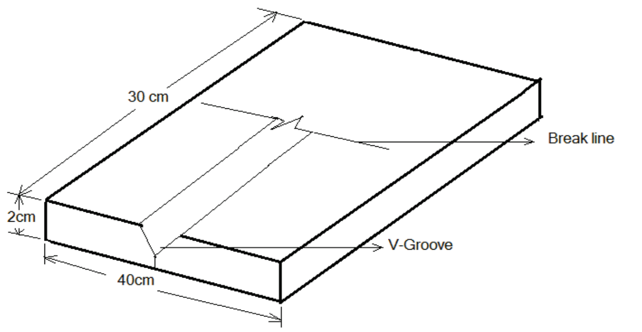

Figure 1 Two pieces of mild steel plates were welded and V-groove of angle for the purpose was 60°

Table 1 Sample values for bead parameters

Sl. No.	Voltage, V	Current, A	Travel speed, cm/min	Penetration, mm	Reinforcement height, mm	Bead width, mm
1	25	350	17	6,70	2,38	17,96

3 The analytical solution to temperature field

As a temperature field solution is aggregation of temperature fields caused by action of applied bead and electric arc:

$$\Delta\vartheta = \Delta\vartheta_{\mathrm{w}}(x,y,z,t) + \Delta\vartheta_{\mathrm{a}}(\tau,\varphi,z,t), \tag{1}$$

where,
$\Delta\vartheta_{\mathrm{w}}(x,y,z,t)$ – change of temperature caused by the heat of molten electrode
$\Delta\vartheta_{\mathrm{a}}(\tau,\varphi,z,t)$ – change of temperature caused by the heat of electric arc.

4 Temperature caused by the heat of electric arc

Heat source shape for this study was assumed as an oval shape, whose equation is

$$ax^2 + (by^2 + cz^2)\cdot \mathrm{e}^{mx} = 1, \tag{2}$$

where a – semi major axis, b – semi minor axis, c – another semi-principal axis of an ellipsoid whose equation is

$$ax^2 + by^2 + cz^2 = 1. \tag{3}$$

Initially proposed is an oval heat source in which heat is distributed in a Gaussian manner throughout the heat source's volume. The heat density $q(x, y, z)$ at a point (x, y, z) within oval shape is given by the following equation:

$$q(x,y,z) = \mathrm{A}\cdot \mathrm{e}^{-(ax^2 + (by^2 + cz^2)\cdot \mathrm{e}^{mx})}, \tag{4}$$

where A is Gaussian heat distribution parameter and a, b, c, m are oval heat source parameters.

If Q_0 is the total heat input, then

$$2Q_0 = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} q(x,y,z)\mathrm{d}x\mathrm{d}y\mathrm{d}z,$$
$$\text{or } \mathrm{A} = \frac{2\sqrt{abc}}{\pi^{\frac{3}{2}}}\cdot\frac{1}{\mathrm{e}^{\frac{m^2}{4a}}}\cdot Q_0. \tag{5}$$

Oval shape heat distribution equation is:

$$q(x,y,z) = \frac{2\sqrt{abc}}{\pi^{\frac{3}{2}}}\cdot\frac{1}{\mathrm{e}^{\frac{m^2}{4a}}}\cdot Q_0\cdot \mathrm{e}^{-(ax^2 + (by^2 + cz^2)\cdot \mathrm{e}^{mx})}, \tag{6}$$

here, $Q_0 = I\cdot V\cdot \eta$; V, I, η – welding voltage, current and arc efficiency respectively.

Arc efficiency is taken as 1 for submerged arc welding process.

4.1 Induced temperature field

Heat conduction in a homogeneous solid is governed by the linear partial differential equation

$$k\nabla^2\vartheta + q = \rho c_p \frac{\partial T}{\partial t}. \tag{7}$$

Analytical solution: Transient temperature field of oval heat source in a semi-infinite body is based on solution for the instant point source that satisfied the following differential equation of heat conduction of fixed coordinates [14].

$$\mathrm{d}\vartheta_{t'} = \frac{\mathrm{d}Q\mathrm{d}t'}{\rho C\pi^{\frac{3}{2}}[4\alpha\pi(t-t')]^{\frac{3}{2}}}\times\exp\left(-\frac{(x-x')^2 + (y-y')^2 + (z-z')^2}{4\alpha(t-t')}\right), \tag{8}$$

where α – thermal diffusivity, C – specific heat, ρ – mass density; t, t' – time; $\mathrm{d}\vartheta_{t'}$ – transient heat source due to the point heat source $\mathrm{d}Q$ at time t'; (x', y', z') – location of instant point heat source $\mathrm{d}Q$ at time t'. Let us consider the solution of the oval heat source as a result of superposition of a series of instant point heat sources over the volume of the distributed Gaussian heat source. Substitute Eq. (6) into Eq. (8) and integration over the volume of the heat source of oval shape gives

$$\mathrm{d}\vartheta_{t'} = \frac{1}{2}\cdot\frac{Q_0\mathrm{d}t'}{\rho C\pi^{\frac{3}{2}}[4\alpha\pi(t-t')]^{\frac{3}{2}}}\times$$
$$\times\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\mathrm{e}^{\left(-\frac{(x-x')^2+(y-y')^2+(z-z')^2}{4\alpha(t-t')}\right)}\times \tag{9}$$
$$\times\left[\frac{2\sqrt{abc}}{\pi^{\frac{3}{2}}}\cdot\frac{1}{\mathrm{e}^{\frac{m^2}{4a}}}\cdot\mathrm{e}^{-(ax'^2+(by'^2+cz'^2)\cdot\mathrm{e}^{mx'})}\right]\mathrm{d}x'\,\mathrm{d}y'\,\mathrm{d}z'.$$

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

$$\Delta\vartheta_{\mathrm{a}}(x,y,z,t) = \int_0^t \frac{1}{2}\cdot\frac{Q_0}{\rho C_p\pi^{\frac{3}{4}}[4\alpha\pi(t-t')]^{\frac{3}{2}}}\times$$
$$\times\left\{\frac{1}{2}\cdot\frac{Q_0\mathrm{d}t'}{\rho C\pi^{\frac{3}{4}}[4\alpha\pi(t-t')]^{\frac{3}{2}}}\cdot\frac{2\sqrt{abc}}{\pi^{\frac{3}{2}}}\cdot\frac{1}{\mathrm{e}^{\frac{m^2}{4a}}}\cdot\right. \tag{10}$$
$$\left.\cdot\frac{\mathrm{e}^{-\frac{by^2}{1+4b\alpha(t-t')}}}{[1+4b\alpha(t-t')]^{\frac{1}{2}}}\cdot\frac{\mathrm{e}^{-\frac{cz^2}{1+4b\alpha(t-t')}}}{[1+4c\alpha(t-t')]^{\frac{1}{2}}}\cdot\frac{\mathrm{e}^{-\frac{a(x-vt')^2}{1+4a'\alpha(t-t')}}}{[1+4a'\alpha(t-t')]^{\frac{1}{2}}}\right\}.$$

Calculation of oval shape bead geometry parameters:

Let the A, B, C be the oval shape bead geometry parameters. In [14], $q(A,0,0) = \mathrm{e}^{\alpha A^2} q(0) = 0{,}05 q(0)$ or $a = \frac{\ln 20}{A^2}$, similarly, $b = \frac{\ln 20}{B^2}$, $c = \frac{\ln 20}{C^2}$, $m = 0{,}3$.

Values A, B, C can be measured from weld bead geometry, B – half of the bead width, C – penetration and A – half of the major axis of oval shape = 1,15×B (experimentally found i.e. through weld pool measurement for submerged arc welding process). Experimentally measured values A, B, C are applied to find out the temperature distribution values of Eq. (16).

In present study electrode is following in curve path. So this path can be assumed in numbers of small straight lines. Let this curve be divided in k number.

For a temporary position the heat source is determined by the relationship:

$$\tau = x - v \cdot \cos \beta_i (t + t_0) - x_{0i}, \tag{11}$$

$$\varphi = y - v \cdot \sin \beta_i (t + t_0) - y_{0i}. \tag{12}$$

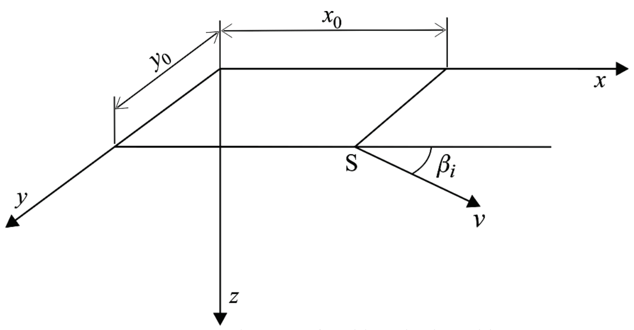

Figure 2 Diagram of making single weld

So, from Eqs. (11) and (12) and fron Figs. 2 and 4 it can be written that

$$\Delta \vartheta_{\mathrm{a}}(\tau,\varphi,z,t) = \sum_{j=1}^{j=k} \int_{j-1}^{j} \int_{0}^{t} \frac{1}{2} \cdot \frac{Q_0}{\rho C_p \pi^{\frac{3}{4}} [4\alpha\pi(t-t')]^{\frac{3}{2}}} \times$$

$$\times \left\{ \frac{1}{2} \cdot \frac{Q_0 \mathrm{d}t'}{\rho C \pi^{\frac{3}{4}} [4\alpha\pi(t-t')]^{\frac{3}{2}}} \cdot \frac{2\sqrt{abc}}{\pi^{\frac{3}{2}}} \cdot \frac{1}{\mathrm{e}^{\frac{m^2}{4a}}} \cdot \right. \tag{13}$$

$$\left. \cdot \frac{\mathrm{e}^{-\frac{b\varphi^2}{1+4b\alpha(t-t')}}}{[1+4b\alpha(t-t')]^{\frac{1}{2}}} \cdot \frac{\mathrm{e}^{-\frac{cz^2}{1+4b\alpha(t-t')}}}{[1+4c\alpha(t-t')]^{\frac{1}{2}}} \cdot \frac{\mathrm{e}^{-\frac{a(\tau - vt')^2}{1+4a'\alpha(t-t')}}}{[1+4a'\alpha(t-t')]^{\frac{1}{2}}} \right\}.$$

5 Temperature caused by the heat of molten electrode

Total heat delivered (calculated by taking integration limit from Fig. 3):

$$q = 8 \int_0^{a^{-1}} \mathrm{d}x \times \int_0^{(\mathrm{e}^{-mx} - (ax)^2)^{0,5} \cdot b^{-1}} \mathrm{d}y \times \int_0^{\left[\mathrm{e}^{-mx} - (ax)^2 - (by)^2\right]^{0,5} \cdot c^{-1}} q(x,y,z) \mathrm{d}z. \tag{14}$$

If we put volumetric heat source $q(x, y, z)$ in point (x', y', z'), temperature increase is equal

$$\Delta \vartheta_{\mathrm{w}}(x,y,z,t) = \Delta \vartheta_{\mathrm{w}}(x,y,z,t) - \vartheta_0 = \frac{1}{\rho C_p (4\alpha\pi t)^{\frac{3}{2}}} \times$$

$$\times 8 \int_0^{a^{-1}} \mathrm{e}^{\frac{(x-x')^2}{4\alpha t}} \mathrm{d}x \times \int_0^{(\mathrm{e}^{-mx} - (ax)^2)^{0,5} \cdot b^{-1}} \mathrm{e}^{\frac{(y-y')^2}{4\alpha t}} \mathrm{d}y \times \tag{15}$$

$$\times \int_0^{\left[\mathrm{e}^{-mx} - (ax)^2 - (by)^2\right]^{0,5} \cdot c^{-1}} q \cdot \mathrm{e}^{\frac{(z-z')^2}{4\alpha t}} \mathrm{d}z.$$

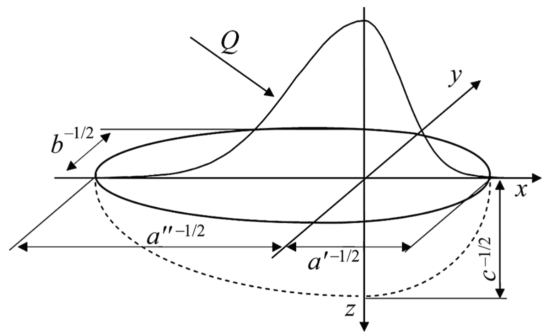

Figure 3 Geometry of weld-oval.
Equation of oval is taken as $ax^2 + (by^2 + cz^2)\mathrm{e}^{mx} = 1$

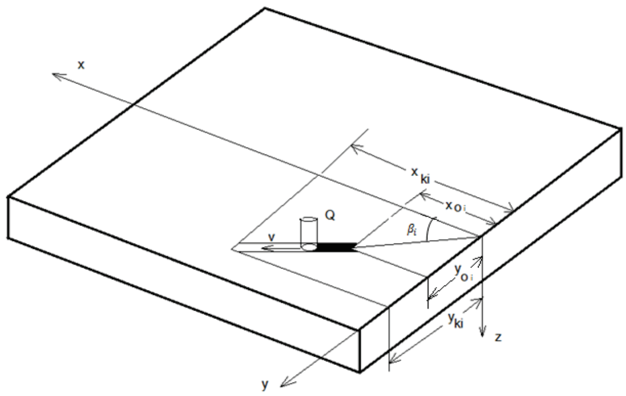

Figure 4 Diagram of making i weld

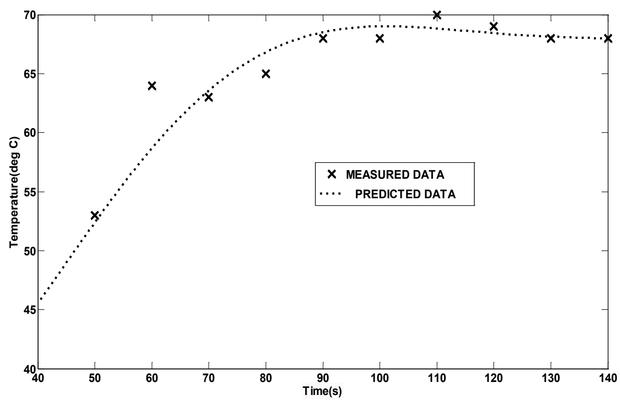

Figure 5 Comparison between predicted and measured transient temperature distribution at point (0; 4,5; 1)

6 Estimated and measured temperature distribution

From Eqs. (13), (14) and (15), estimated temperature distribution on welded plates when position of electrode was (1 cm, 3 cm, 0). Comparison of estimated and measured temperature distribution of welded plate is shown in Figs. 5 and 6. To calculate temperature distribution, value of thermal conductivity of welded plates is taken as 51 W/(m·K), specific heat is taken as 565 J/(kg·K), thermal expansion coefficient is taken as 10×10^{-6}/°C, thermal diffusivity is taken as 0,000015 m^2/s.

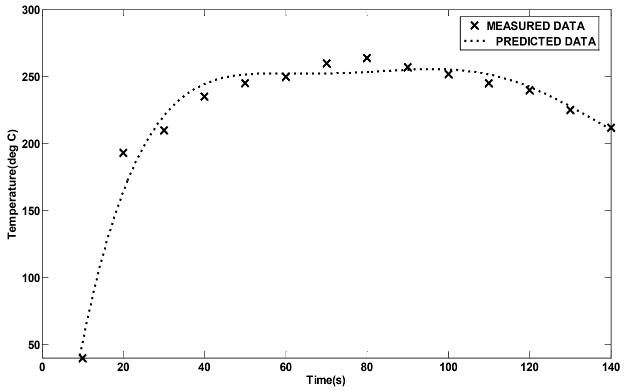

Figure 6 Comparison between predicted and measured transient temperature distribution at point (1 cm, 2 cm, 0)

7 Conclusion

Comparison between measured temperature field and predicted data through analytical method considering heat radiation from electrode and heat transfer from molten electrode was made. Good agreement between predicted and measured data was achived. The validated analytical predictions indicate that the present solution could offer a good prediction for transient temperatures near the weld pool, as well as away from welding path. The newly developed heat source model has predictive potential for various welding simulations.

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