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CRITICAL ANALYSIS OF MOVING HEAT SOURCE SHAPE FOR ARC WELDING PROCESS OF HIGH DEPOSITION RATE

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Original scientific paper
Analysis of heat source shape is important for comprehending Submerged Arc Welding Process. Here an attempt is made to investigate into the analytical solution of the thermal field related to a high deposition rate based process like SAW. It is assumed that a moving heat source follows Gaussian distribution. The realistic assumptions of the shape parameters are made to describe the process theoretically. It is opined that for SAW process the most appropriate heat source shape is approximately oval.

Keywords: *Gaussian heat distribution, oval heat source shape, Submerged Arc Welding*

Kritična analiza pokretnih oblika izvora topline za proces lučnog zavarivanja visoke brzine taloženja

Izvorni znanstveni članak
Analiza oblika izvora topline važna je za razumijevanje EPP proces zavarivanja. Ovdje se u analitičkom rješenju toplinskog polja pokušalo istražiti odnos procesa utemeljenog na visokoj brzini taloženja poput EPP. Pretpostavljeno je da pokretni izvor topline slijedi Gaussovu raspodjelu. Realne pretpostavke parametara oblika napravljene su radi teorijskog opisa procesa. Iznijeto je mišljenje da je za EPP proces najprikladniji oblik izvora topline približno ovalni.

Ključne riječi: *EPP zavarivanje, Gaussova raspodjela topline, ovalni oblik izvora topline*

1 Introduction

Two approaches in existing literature review are pre dominant for modelling thermal transport in welding processes. One approach is numerical [1 ÷ 10] and the other is based on analytical solution [11 ÷ 25]. More than four decades ago, Rosenthal [11] first attempted to find out transient temperature distribution of welded plate considering moving point heat source. After that many researchers attempted to find out transient temperature distribution of welded plate through analytical method considering moving 2D [11 ÷ 13] and 3D [14 ÷ 27] heat source. Rykalin [27] pointed out that to find out transient temperature distribution the following factors should be considered:
– variable thermal properties,
– latent heat of fusion,
– pattern of heat distribution.

Previously, no one considered all these factors to find out transient temperature distribution of welded plates. Most of the researchers also did not consider the convective heat loss during the welding operation. In present work, heat distribution shape was considered and very good agreement between predicted and measured temperature data was achieved.

2 Experimental procedure

MEMCO semi-automatic welding machine with constant voltage, retifyer type power source with a 1200-A capacity was used to join C-Mn steel plates. ESAB SA1 (E8), 0,315 cm diameter, cooper coated electrode in coil form and ESAB brand, basic fluoride type granular flux were used. The experiments were conducted as per the design matrix randomly to avoid errors due to noise factors. Two pieces of C-Mn steel plates (30×15×2 cm) were cut and V grooves of angle 60° were made as per the standards. The chemical composition of work piece material is described in Tab. 1. 1 mm root opening was selected to join the plates in the flat position keeping the electrode positive and perpendicular to the plate.

Table 1 Chemical composition of C-Mn steel work piece (in wt. %)

C	Sn	Mn	P	S
0,19	0,37	1,58	0,023	0,027
Cr	Ni	Mo	Cu	Al
0,06	0,03	0,01	0,04	0,046

Table 2 Observed Values for Bead Parameters for HAZ analysis

Sl.No.	Voltage (*V*) (V)	Current (*I*) (A)	Travel Speed (*S*) (cm/min)	Penetration (*P*) (mm)	Reinforcement Height (*L*) (mm)	Bead Width(*B*) (mm)	HAZ width (*HW*) (mm)
1	25	350	17	6,70	2,38	17,96	1,20
2	35	350	17	3,72	2,34	21,90	1,32
3	25	450	17	6,69	3,16	21,00	1,40
4	35	450	17	8,26	2,76	30,92	2,18
5	25	350	30	5,28	1,00	13,94	1,05
6	35	350	30	4,58	1,78	20,12	1,33
7	25	450	30	6,60	2,25	15,90	1,20
8	35	450	30	7,78	1,94	22,66	1,33

The job was firmly fixed to a base plate and then the submerged arc welding was finally carried out. Temperatures were measured at different points of the welded plates as shown in Fig.1by infrared thermometers (OMEGA SCOPE OS524E, temperature range 2482 °C, accuracy is ±1 % rdg or 2 °C whichever is higher, resolution 1 °C, response time 10 ms). Temperature distribution on the welded plate is shown in Fig. 2. The job was cut at three sections of welded plates. The samples were prepared by standard metallographic process and the average values of the penetration, reinforcement height are measured using digital venire calliper of least count 0,02 mm. The measured values of weld dimensions and corresponding welding conditions are described in Tab. 2.

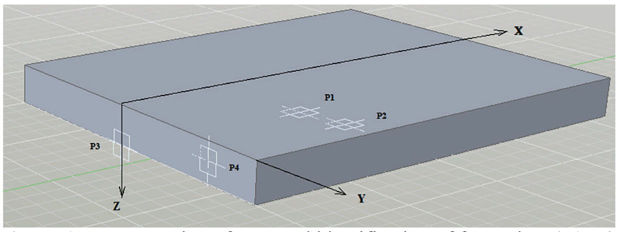


Figure 1 Representation of axes and identification of few points (P1, P2, P3, P4) where reading of temperature was taken

3 Analytical solution of temperature field during welding

Let us consider a fixed Cartesian reference frame x, y, z as shown in Fig. 1. 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 as shown in Fig. 3 is given by the following equation:

$$q(x,y,z)=A\mathrm{e}^{-\left(ax^2+\left(by^2+cz^2\right)\mathrm{e}^{mx}\right)}, \tag{1}$$

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:

$$Q_0=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}q(x,y,z)\mathrm{d}x\mathrm{d}y\mathrm{d}z$$

or

$$A=\frac{2\sqrt{abc}}{\pi^{\frac{3}{2}}}\cdot\mathrm{e}^{-\frac{m^2}{4a}}\cdot Q_0.$$

Oval shape heat distribution equation is:

$$q(x,y,z)=\frac{2\sqrt{abc}}{\pi^{\frac{3}{2}}}\cdot Q_0\mathrm{e}^{-\left(ax^2+\left(by^2+cz^2\right)\mathrm{e}^{mx}\right)}. \tag{2}$$

Here, $Q_0=I\times V\times\eta$; V, I,η = welding voltage, current and arc efficiency respectively. Arc efficiency is taken 1 for submerged arc welding process. Analytical solution: Transient temperature field of oval shape 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].

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

where α = thermal diffusivity, C = specific heat, ρ = mass density; t, t' = time; $\mathrm{d}T_{t'}$ = transient temperature change 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 an instant oval heat source as a result of superposition of a series of instant point heat source over the volume of the distributed Gaussian heat source. Substitute Eq. (2) into Eq. (3) and integration over the volume of the heat source of oval shape gives:

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

where:

$$\begin{aligned}I_z&=\int_{-\infty}^{\infty}\mathrm{e}^{-\frac{(z-z')^2}{4\alpha(t-t')}}\cdot\mathrm{e}^{\left(\mathrm{e}^{cz'}\right)\mathrm{e}^{mx'}}\mathrm{d}z'=\\&=\frac{\sqrt{4\pi a\,(t-t')}}{\sqrt{4c\alpha\mathrm{e}^{mx'}(t-t')+1}}\cdot\mathrm{e}^{-\frac{c\mathrm{e}^{mx'}z^2}{4c\mathrm{e}^{mx'}\alpha\,(t-t')+1}}\end{aligned} \tag{5}$$

$$\begin{aligned}I_z&=\int_{-\infty}^{\infty}\mathrm{e}^{-\frac{(y-y')^2}{4\alpha(t-t')}}\cdot\mathrm{e}^{\left(\mathrm{e}^{by'}\right)\mathrm{e}^{mx'}}\mathrm{d}y'=\\&=\frac{\sqrt{4\pi a\,(t-t')}}{\sqrt{4b\alpha\mathrm{e}^{mx'}(t-t')+1}}\cdot\mathrm{e}^{-\frac{by^2}{4b\mathrm{e}^{mx'}\alpha\,(t-t')+1}}\end{aligned} \tag{6}$$

$$I_x=\int_{-\infty}^{\infty}\mathrm{e}^{-\frac{(x-x')^2}{4\alpha\,(t-t')}}\cdot\left[\mathrm{e}^{-\left(ax'^2\right)}\right]I_yI_z\mathrm{d}x'. \tag{7}$$

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

$$\begin{aligned}T-T_0&=\int_0^t\frac{1}{2}\cdot\frac{Q_0}{\rho C\pi^{\frac{3}{2}}\left[4\pi\alpha(t-t')\right]^{3/2}}\cdot\frac{2\sqrt{abc}}{\pi^{\frac{3}{2}}}\cdot\\&\cdot\mathrm{e}^{-\frac{m^2}{4a}}\cdot Q_0\cdot I_{x_1}\cdot I_y\cdot I_z\mathrm{d}t',\end{aligned} \tag{8}$$

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

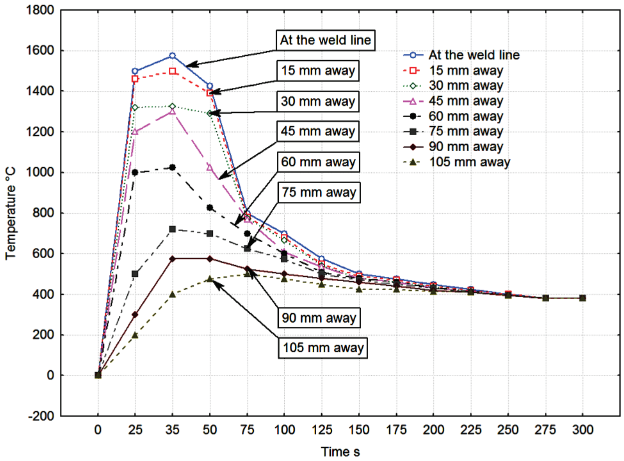


Figure 2 Temperature distribution at various points on the plate surface for square butt welding of 20 mm thick plate w. r. t. time

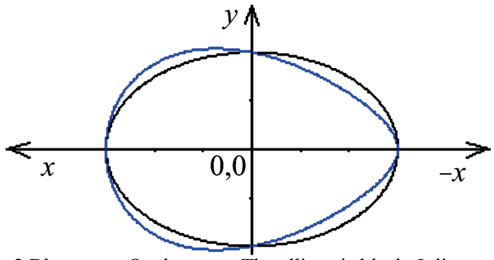


Figure 3 Blue curve Oval curves. The ellipse is black. It lies under the ellipse on the right side of the y-axis .Equation of this oval shape curve (blue curve) is ax^2+by^2 (f(x)) =1

4 Results and discussions

4.1 Calculation of oval shape bead geometry parameters

Let the A, B, P be the Oval Shape Bead Geometry parameters. In literature (Goldak and Akhlaghi, 2005) they are $q(A,00) = q(0)\,\mathrm{e}^{aA^2} = 0{,}05\, q(0)$,

$$a=\frac{20}{A^2};\ b=\frac{20}{B^2};\ c=\frac{20}{P^2}.$$

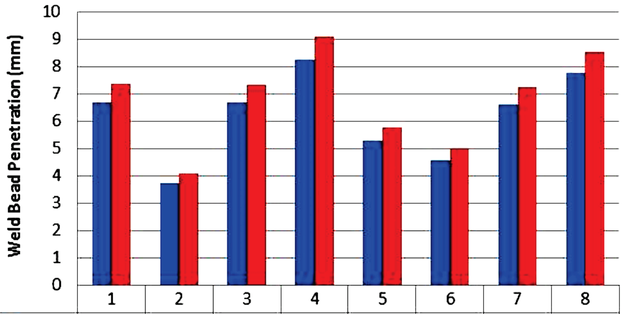
Values A, B, P can be measured from weld bead geometry, B = half of the bead width, P = Penetration and A = half of the major axis of oval shape. Experimentally measured values A, B, P are applied to find out the values temperature distribution of Eq. (8).

4.2 Penetration prediction

Weld Bead Penetration of a C-Mn steel is the region heated from atmospheric temperature (i.e. 303 K) to the melting point temperature of welded materials (i.e. 1684 K). Putting these values in the Eq. (8) penetration(s) have been calculated at y = 0, x = vt', t = t', which is shown in Fig. 4.

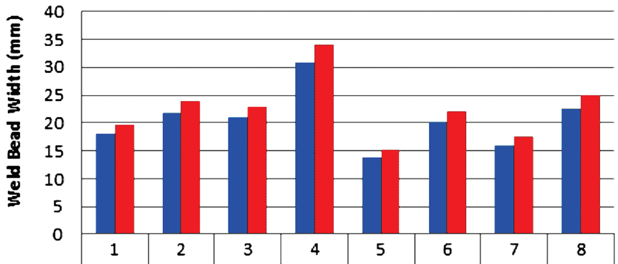
4.3 Weld bead width prediction

Weld Bead Penetration of a C-Mn steel is the region heated from atmospheric temperature (i.e. 303 K) to the temperature of the melting point of welded materials (i.e. 1684 K). Putting these values in the Eq. (8) penetration(s) have been calculated at y = 0, x = vt', t = t', which are tabulated below. Weld Bead Width of a structural steel is the region heated from atmospheric temperature (i.e. 303 K) to the temperature of the melting point temperature of welded materials (i.e. 1684 K). Putting these values in the Eq. (8) half of weld bead(s) have been calculated at z = 0, x = vt', t = t'. Satisfactory agreement between predicted and measured data was achived which is shown in Fig. 5.



	1	2	3	4	5	6	7	8
Series1	6,7	3,72	6,69	8,26	5,28	4,58	6,6	7,78
Series2	7,36	4,1	7,34	9,08	5,78	5,03	7,26	8,55

Figure 4 Comparison of predicted and experimental results for Weld Bead Penetration



	1	2	3	4	5	6	7	8
Series1	17,96	21,9	21	30,92	13,94	20,12	15,9	22,66
Series2	19,73	23,91	23	34,01	15,29	22,09	17,47	24,9

Figure 5 Comparison of predicted and experimental values of Weld Bead Width

5 Conclusions

Heat distribution on welded plate is of Oval shape for Submerged Arc Welding process and the heat source related parameters of this heat source can be measured from the dimension of bead geometry.

1. Transient temperature distribution on welded plate can be calculated with the help of Gaussian Oval shape heat distribution technique.
2. In this study, analytical solutions for the transient temperature field of a semi-infinite body subjected to 3-D power density moving heat source (such as oval shape heat source, which is for the first time attempted in this work) were found and experimentally validated. The analytical solution for oval shape heat source was used to calculate transient temperatures at selected points on mild steel plates which were welded by taking x-axis along welding line. The origin is the starting point of welding, y-axis is perpendicular to the welding line and z-axis towards plate thickness. Both analytical and experimental results from this study have shown that the present analytical solution could offer a fair level of prediction for transient temperatures near the weld pool, as well as simulate the complicated welding path. Furthermore, 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 modelling.

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