ISSN 1330-3651
UDC/UDK 621.791.75:536.24

PREDICTION OF WELD BEAD PARAMETERS, TRANSIENT TEMPERATURE DISTRIBUTION & HAZ WIDTH OF SUBMERGED ARC WELDED STRUCTURAL STEEL PLATES

Aniruddha Ghosh, Somnath Chattopadhyaya, Sergej Hloch

Original scientific paper
In a submerged arc welding process, the concept of temperature distribution is essential in order to control the HAZ (heat-affected zone) dimensions and get the required bead size and quality. In this paper, an analytical solution for moving heat source with Gaussian distribution of inside volume of central conicoidal shape is derived. Heat transfer in welded plates during welding is assumed to be the conductive heat transfer of a semi infinite body. With the help of this analytical solution, the transient temperature distribution, the HAZ width, the weld bead dimensions are estimated. Good compatibility between predicted and experimental values is achieved.

Keywords: *Gaussian heat distribution, HAZ, Submerged Arc Welding (SAW), transient temperature distribution, weld bead parameters*

Predviđanje parametara utora zavarenog spoja, raspodjela prijelazne temperature i širina ZUT-a ploča konstrukcijskog čelika zavarenog pod troskom

Izvorni znanstveni članak
U procesu elektrolučnog zavarivanja taljivom žicom pod zaštitnom troskom (EPT), koncept raspodjele temperature je bitan za kontrolu dimenzija ZUT-a (zone utjecaja topline) i dobivanje potrebne veličine i kvalitete utora. U ovom radu, izvedeno je analitičko rješenje za premještanje izvora topline s Gaussovom raspodjelom unutar volumena središnjeg konusnog oblika. Prijenos topline u zavarenim pločama za vrijeme zavarivanja pretpostavljen je kao da je prijenos vodljive topline polu-beskonačnog tijela. Uz pomoć ovog analitičkog rješenja, procijenjene su raspodjela prijelazne temperature, širina ZUT-a te dimenzije utora zavarenog spoja. Postignuta je dobra sukladnost između predviđenih i eksperimentalnih vrijednosti.

Ključne riječi: *Gaussova raspodjela topline, parametri utora zavarenog spoja, raspodjela prijelazne temperature, ZUT, zavarivanje pod troskom (EPT)*

1 Introduction

This manufacturing revolution is now, the same as in the past, centred on the use of new tools and new forms of energy. The result is the introduction of new manufacturing processes used for forming and joining [1], and for material removal, known today as non-traditional manufacturing processes. One of the methods of joining is the submerged arc welding, which is a high-productivity welding method in which the arc is struck beneath the covering layer of flux [2]. It is commonly used to join plates of higher thickness in load bearing components. The submerged arc welding is a high deposition rate based welding process. The SAW process is similar to the MIG (metal inert gas) welding where the arc is formed between a continuously-fed wire electrode and the work piece and the weld is formed by the melting of the work piece and the wire [3]. However, in the Submerged Arc Welding process, a shielding gas is not required as the layer of flux generates the gases and slag to protect the weld pool and the hot weld metal from contamination. Flux plays an additional role in adding alloying elements to the weld pool. The submerged-arc welding (SAW) process is popular because of its ability to match the chemistry and physical properties of the base material. This ability allows a multitude of possible weld-wire and flux combinations. These combinations can be easily sorted and matched to specific applications. Submerged arc welding provides a purer and cleaner high volume weld and also faster than with the traditional welding methods [4 ÷ 12]. Lots of critical sets of input parameters (i.e. current, voltage, travel speed, stick out, electrode wire diameter, polarity, etc.) are involved in a Submerged Arc Welding operation which forms the heat input function and the shape of heat source which varies with the change of input parameters of the SAW process. It is the main reason for considering a central conicoidal heat source [13, 14]. Parameters controlling the heat source are obtained through the measurement of weld bead geometry [15 ÷ 21, 22, 23]. The derived analytical solution has agreements with the measured experimental values. In previous works a particular shape of heat source (i.e. elliptical heat source) was chosen. Nyguyen, et al. [24] derived analytical solution for the transient temperature field of the semi infinite body subjected to 3-D power density of a moving 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. Practically in the SAW process the shape of heat source changes with the change of input parameters [16] and that is why the central conicoidal heat source is assumed in present work. This (consideration of Central Conicoidal Heat Source) is the basic difference of the present work with respect to the previous works. Prediction of the HAZ width, weld bead geometry dimensions are made with the help of three dimension transient temperature distribution equations and validation is made through experimental results

2 Experimental procedure

The experiments were conducted as per the design matrix randomly to avoid errors due to noise factors. The structural steel work piece (300×150×20 mm - 2 pieces) wais cut and V groove of angle 60° as per the standard wais prepared. The workpiece was firmly fixed to a base plate by means of tack welding and then the submerged arc welding was finally carried out. The welding parameters were recorded during actual welding to determine their fluctuations, if any. The slag was removed and the job was allowed to cool down. Welding was carried out for the square butt joint configuration. The job was cut at three sections by a hacksaw cutter and the average values of the penetration, reinforcement height and width were recorded using digital venire calliper of least count 0,02 mm. During welding, temperatures were recorded at different points of the welded plates by Infrared thermometer and with the optical research microscope HAZ width(s) were measured.

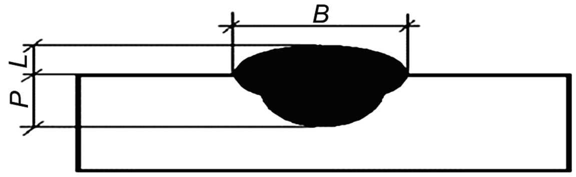

Figure 1 Bead geometry, *P* - penetration, *L* - reinforcement height, *B* - bead width

Table 1 Observed Values for Bead Parameters for HAZ analysis

Sl.No.	Voltage / V	Current / A	Travel Speed / cm/min	Penetration / mm	Reinforcement height / mm	Bead width / mm	HAZ width / 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

3 Gaussian heat distribution

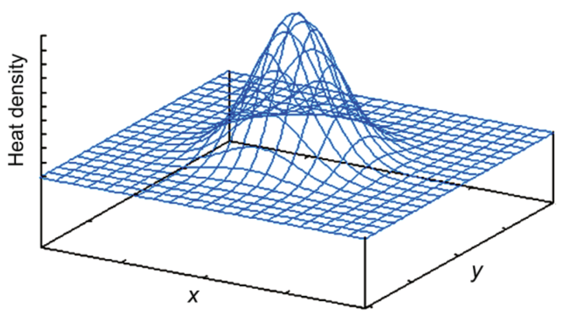

Figure 2 Heat density distribution (inside volume of central conicoidal shape) pattern on welded plates, when moving electrode of submerged arc welding is in the middle position of welding line.

Let us consider a fixed Cartesian reference frame *x*, *y*, *z*. Initially proposed is a semi-Central Conicoidal 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*) with in semi-Central Conicoid is given by the following equation:

$$q(x,y,z) = q(0)\mathrm{e}^{-(ax^2+by^2+cz^2)}. \qquad (1)$$

[Where $q(0)$ is Gaussian heat distribution parameter and a, b, c are central Conicoidal heat source parameters]

If Q_0 is the total heat input, then:

$$2Q_0 = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} q(x,y,z)\mathrm{d}x\mathrm{d}y\mathrm{d}z$$

$$\text{or } q(0) = \frac{2\sqrt{abc}}{\pi^{3/2}} \times Q_0$$

$$\therefore q(x,y,z) = \frac{2\sqrt{abc}}{\pi^{3/2}} \times Q_0 \mathrm{e}^{-(ax^2+by^2+cz^2)}. \qquad (2)$$

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.

$$q(x,y,z) = \frac{2\sqrt{abc}}{\pi^{3/2}} \times Q_0 \mathrm{e}^{-(ax^2+by^2+cz^2)}. \qquad (3)$$

Analytical solution: Transient temperature field of central conicoidal 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 [3].

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

Where α = thermal diffusivity; c_p = specific heat; ρ = mass density; t, t' = time; $\mathrm{d}T_{t'}$ = transient temperature change due to the point heat source dQ at time t'; (x', y', z') = location of instant point heat source dQ at time t'. Let us consider the solution of an instant central conicoidal 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. (3) into Eq. (4) and integration over the volume of the heat source shapes gives

$$\mathrm{d}T_{t'} = \frac{1}{2} \times \frac{2\sqrt{abc}}{\pi^{3/2}} \times \frac{Q_0\mathrm{d}t'}{\rho c_\mathrm{p}\pi^{3/2}[4\alpha\pi(t-t')]^{3/2}} \times$$
$$\times q(0)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathrm{e}^{\left(-\frac{(x-x')^2+(y-y')^2+(z-z')^2}{4\alpha(t-t')}\right)} \times \qquad (5)$$
$$\times\left(\mathrm{e}^{-(ax'^2+by'^2+cz'^2)}\right)\mathrm{d}x'\mathrm{d}y'\mathrm{d}z'.$$

Here,

$$\int_{-\infty}^{\infty} \mathrm{e}^{-\frac{(x-x')^2}{4\alpha(t-t')}} \times \mathrm{e}^{-ax'^2}\mathrm{d}x' = \sqrt{\pi}\sqrt{\frac{4\alpha(t-t')}{4a\alpha(t-t')+1}}\mathrm{e}^{-\frac{x^2}{4a\alpha(t-t')+1}}$$

$$\int_{-\infty}^{\infty} \mathrm{e}^{-\frac{(y-y')^2}{4\alpha(t-t')}} \times \mathrm{e}^{-by'^2}\mathrm{d}y' = \sqrt{\pi}\sqrt{\frac{4\alpha(t-t')}{4b\alpha(t-t')+1}}\mathrm{e}^{-\frac{y^2}{4b\alpha(t-t')+1}}$$

$$\int_{-\infty}^{\infty} \mathrm{e}^{-\frac{(z-z')^2}{4\alpha(t-t')}} \times \mathrm{e}^{-cx'^2} \mathrm{d}z' = \sqrt{\pi}\sqrt{\frac{4\alpha(t-t')}{4c\alpha(t-t')+1}}\mathrm{e}^{-\frac{z^2}{4c\alpha(t-t')+1}}$$

So,

$$\mathrm{d}T_{t'} = \left[\frac{\sqrt{abc}}{\pi^{3/2}} \times \frac{Q_0}{\rho c_\mathrm{p}} \times \sqrt{\frac{1}{4a\alpha(t-t')+1}} \times \mathrm{e}^{-\frac{x^2}{4a\alpha(t-t')+1}} \times \right.$$
$$\times \sqrt{\frac{1}{4b\alpha(t-t')+1}} \times \mathrm{e}^{-\frac{y^2}{4b\alpha(t-t')+1}} \times \tag{6}$$
$$\left. \times \sqrt{\frac{1}{4c\alpha(t-t')+1}} \times \mathrm{e}^{-\frac{z^2}{4c\alpha(t-t')+1}} \right] \mathrm{d}t'.$$

When the 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

$$T(x,y,z,t) - T_0 = \left[\int_0^t \frac{\sqrt{abc}}{\pi^{3/2}} \times \frac{Q_0}{\rho c_\mathrm{p}} \times \sqrt{\frac{1}{4a\alpha(t-t')+1}} \times \right.$$
$$\times \mathrm{e}^{-\frac{(x-vt)^2}{4a\alpha(t-t')+1}} \times \sqrt{\frac{1}{4b\alpha(t-t')+1}} \times \mathrm{e}^{-\frac{y^2}{4b\alpha(t-t')+1}} \times \tag{7}$$
$$\left. \times \sqrt{\frac{1}{4c\alpha(t-t')+1}} \times \mathrm{e}^{-\frac{z^2}{4c\alpha(t-t')+1}} \right] \mathrm{d}t'.$$

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 Calculation of central conicoidal shape heat source parameters

Let the A, B, C be the central Conicoidal Shape Bead Geometry parameters. It has been found from literature [2] that, $\mathrm{q(A,0,0)} = \mathrm{q(0)e}^{aA^2} = 0{,}05q(0)$

$$\therefore a = \frac{\ln 20}{A^2}. \text{ Similarly, } b = \frac{\ln 20}{B^2}, c = \frac{\ln 20}{C^2}.$$

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 central Conicoidal shape. Experimentally measured values A, B, C are applied to find out the values of temperature distribution of equation (7). When, $x = vt'$, $y = 0$, $z = 0$, predicted transient temperature distributions along welding line with the help of equation (7) are tabulated below.

Table 2 Comparison of predicted and experimental data of temperature distribution along welding line

Time / s	Measured temperature data / °C	Predicted temperature data / °C
0	0	0
6	1900	1815
12	2120	2020
18	2200	2114
24	2290	2172
30	2400	2212

5 Prediction of HAZ width

Putting $x = vt'$, $z = 0$ and $t = 30$ s, $T(x, y, z, t) = T_1 = 1684$ K, $T(x, y, z, t) = T_2 = 973$ K, $T_0 = 303$ K in the Eq. (7) we get y_1, y_2 and $y_1 - y_2$ = HAZ width. Where $y = y_1$ when $T(x, y, z, t) = T_1$ and $y = y_2$ when $T(x, y, z, t) = T_2$.

Table 3 Comparison of predicted and measured HAZ width

No.	Measured HAZ width	Predicted HAZ width	% of error
1	1,20	1,44	20
2	1,32	1,48	12
3	1,40	1,62	16
4	2,18	2,59	19
5	1,05	1,26	20
6	1,33	2,53	9
7	1,20	1,43	19
8	1,33	1,50	13

6 Prediction of weld bead penetration

Putting $x = vt'$, $z = 0$ and $t = 30$ s, $T = T_1 = 1684$ K, $T_0 = 303$ K in the equation (7) we get y_1, and y_1 = half of the weld bead width.

Table 4 Comparison of predicted and experimental values of weld bead width

Weld bead width / mm (Experimental values)	Weld bead width / mm (Predicted values)	% error
17,96	21,01	17
21,90	25,84	18
21,00	25,20	20
30,92	36,79	19
13,94	15,89	14
20,12	24,14	20
15,90	18,60	17
22,66	26,97	19

7 Conclusion

This type of numerical investigation was made to estimate three dimensional transient heat conduction fields in a semi infinite metallic solid because the surface heat transfer strongly affected the temperature distribution in the welded plates. 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 central Conicoidal heat sources) were found and experimentally validated. The analytical solution for the central conicoidal heat source was used to calculate transient temperatures at selected points on mild steel plates which were welded by taking the *x*-axis along the welding line, origin is starting point of welding, *y*-axis is perpendicular to welding line and *z*-axis towards plate thickness. Both numerical and experimental results from this study have shown that the present analytical solution can help to predict the transient temperatures near the weld pool. These newly found solutions will also be helpful to predict heat affected zone, weld bead parameters etc.

8 References

[1] Abid, M.; Nash, D. H. Risk Assessment studies for Gasketed and Non-gasketed Bolted Pipe Joints, International Pipeline Conference (IPC2002), Calgary Canada, Sep 29 w Oct 3 2002. Proceedings of IPC2002/IPC-27386 2002; pp. 1-11.

[2] Nash, D. H.; Abid, M. Surface sensitivity study of non-gasketed flange joint. // J Process Mech Eng; Part-E 2004; E4:218.

[3] Gaćeša, B.; Milošević-Mitić, V.; Maneski, T.; Kozak, D.; Sertić, J. Numerical and experimental strength analysis of fire-tube boiler construction. // Tehnički vjesnik - Technical Gazette. 18, 2(2010), pp. 237-242.

[4] Mateša, B.; Kozak, D.; Stoić, A.; Samardžić, I. The influence of heat treatment by annealing on clad plates residual stresses. // Metalurgija. 50, 4(2011), pp. 227-230.

[5] Brickstad, B.; Josefson, B. L. A parametric Study of Residual Stresses in Multi-pass Butt-Welded stainless steel pipes. // Int J Pres Vessels Piping 1998;75:11-25.

[6] Rybicki, E. F.; Schmueser, D. W.; Stonesifer, R. W.; Groom, J. J.; Mishaler, H. W. A Finite Element Model for Residual Stresses and Deflections in Girth-Butt Welded Pipes. Trans ASME J Press Vessel Technol 1978;100:256-262.

[7] Rybicki, E. F.; McGuire, P. A.; Merrick, E.; Wert, J. The Effect of Pipe Thickness on Residual Stresses due to Girth Welds. ASME J Press Vessel Technol 1982;104:204-209

[8] Rybicki, E. F.; Stonesifer, R. B. Computation of residual stresses due to multipass welds in piping system. Trans ASME J Press Vessel Technol 1979;101:149-154.

[9] Kozak, D.; Gubeljak, N.; Konjatić, P.; Sertić, J. Yield load solutions of heterogeneous welded joints. // International Journal of Pressure Vessels and Piping. 86, 12(2009), pp. 807-812.

[10] Karlsson, L.; Jonsson, M.; Lindgren, L. E.; Nasstrom, M.; Troive, L. Residual stresses and deformations in a welded thin-walled pipe. In: Rybicki E., Shiratori E., Widera G. E. O., Miyoshi T., editors. ASME pressure wessels and piping conference 1989. Weld residual stresses and plastic deformation, PVP-vol. 173. Hawai: Honolulu; 1989. pp. 7-14.

[11] Dong, Y.; Hong, J.; Tasi, C.; Dong, P. Finite element modeling of residual stresses in Austenitic stainless steel pipe girth welds. // AWS Weld J, Weld Res Suppl 1997; 442:449-444.

[12] Karlsson, R. I.; Josefson, B. L. Three dimensional finite element analysis of temperature and stresses in single-pass butt-welded pipe. // Trans ASME J Press Vessel Technol 1990; 112:76-84.

[13] Fricke S, Keim E, Schmidt J. Numerical weld modeling-a method for calculating weld-induced residual stresses. Nucl Eng Des 2001; 206: 139-50

[14] Siddique, M.; Abid, M.; Junejo, H. F.; Mufti, R. A. 3-D finite element simulation of welding residual stresses in pipe-flange joints: effect of welding parameters. Mater Sci Forum 2005; 490–491:79-84.

[15] Ghosh, A.; Chattopadhyaya, S. Prediction of HAZ Width of Submerged Arc Welded Plates. // Advanced materials research, Vols. 584-286(2011), pp. 2481-2484.

[16] Ghosh, A.; Chattopadhyaya, S. Prediction of Weld Bead Penetration, Transient Temperature Distribution& HAZ width of Submerged Arc Welded Structural Steel Plates. // Defect and Diffusion Forum Vols. 316-317 (2011), pp. 135-152

[17] Jonsson, M.; Karlsson, L.; Lindgren, L. E. Simulation of tack welding procedures in Butt joint welding of plates. // AWS Weld J, Weld Res Suppl 1995; 296s-3301.

[18] Jiang, W.; Yahiaoui, K.; Hall, F. R. Finite Element Predictions of Temperature Distributions in a Multipass Welded Piping Branch Junction. // Trans ASME J Press Vessel Technol 2005; 127(1):7-12.

[19] Sattari-Far, I.; Javadi, Y. Influence of welding sequence on welding distortions in pipes. // J Pressure Vessel and Piping 2008; 85:265-274.

[20] ANSYS User's Manual, ANSYS User's Manual, SAS IP inc., 1998.

[21] Goldak, J.; Chakravarti, A.; Bibby, M. A new finite element model for welding heat sources. // Metall Trans B 1984; 15B: 299-305.

[22] Lindgren, L. E. Finite element modeling and simulation of welding part 2: improved material modeling. J Thermal Stress, 24, (2001), pp. 195-231.

[23] Lindgren, L. E.; Hedblom, R. Modelling of addition of filler material in large deformation analysis of multipass welding. Commun Numer Methods Eng, 17, (2001), pp. 647-657.

[24] Nguyen, N. T. et al. Analytical Solution for Transient Temperature of Semi-Infinite Body Subjected to 3-D Moving Heat Sources. // Welding Research, (1999), pp. 265-274.

Authors' addresses

Aniruddha Ghosh
Assistant Professor in Mechanical Engineering
Government College of Engineering & Textile Technology
Berhampore, WB, India
a_ghosh74@yahoo.com
phone: +919475768226

Somnath Chattopadhyaya
Associate Professor
Indian School of Mines
Dept of ME &MME
Dhanbad, India
somuismu@gmail.com

Sergej Hloch
Faculty of Manufacturing Technologies
of Technical Universtity of Košice with a seat in Prešov
Bayerova 1, 080 01 Prešov
Slovak Republic
hloch.sergej@gmail.com