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PREDICTION AND OPTIMIZATION OF HEAT AFFECTED ZONE WIDTH FOR SUBMERGED ARC WELDING PROCESS

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ABSTRACT

- Control of heat affected zone (HAZ) width is very essential for getting required weld bead size and quality. Conditions must be found out that will ensure a predictable and reproducible weld bead that is essential for obtaining repeated, expected cost effective, high quality welded joint. An attempt has been made in present work to find out relation between process control factors i.e. arc voltage, wire feed rate, travel speed, stick out, and heat input and HAZ width. Prediction of HAZ width through analytical solution of heat conduction equation has also been made. Optimum setting of process control variables for minimum HAZ width has been found out through graphical technique.

- *Key words*: HAZ width, Submerged Arc Welding process, transient temperature distribution, regression model, optimization through graphical technique.

INTRODUCTION

- Submerged arc welding (SAW) is a high quality, high deposition rate welding process commonly used to join plates of higher thickness in load bearing components. This process of arc welding provides a purer and cleaner high volume weldment that has relatively a higher material deposition rate compared to the traditional welding methods. Submerged Arc Welding Process is one of the important fabrication processes in industry as it has inbred advantage [1, 2]. Use of this technology has huge economic and social implications in the national perspective. A common issue in the application of SAW process raises a concern about the uncertainties involved with the heat affected zone (HAZ) in and around the weldment. The most intriguing issue is about HAZ softening that imparts some uncertainties in the welded quality. It increases the probability of fatigue failures at the weakest zones caused by the heating and cooling cycle of the weld zone. It is observed that a refined microstructure of the HAZ, imparts largely the intended properties of the welded joint [3].

- For the case SAW joint, engineers repeatedly face the problem to select the appropriate process control parameters for getting optimum value of HAZ width [4]. In order to bring out an appropriate combination of SAW parameters and a methodology to control such parameters an in depth investigations and characterizations of HAZ softening zone are necessary to enrich this Submerged Arc Welding technology.
- In Submerged Arc welding process, major process control parameters are arc voltage and travel speed, wire feed rate, stick out etc. They all affect the bead shape, depth of penetration and chemical composition of the deposited weld metal. Another very critical issue in the understanding of the joint performance obtained from SAW process rests on the analysis of heat affected zone. It is difficult for the operator to observe the weld pool during the process. So, better control comes from SAW process parameter settings than dependence on the operator's expertise. The HAZ has various regions which influence the ability of the joint to provide crack resistance and uniform strength in both the directions of the weld [3].

- The bead width and depth of penetration, measured by infrared thermal imaging technique (IRTI technique), were also found to influence the quality of SAW process [5].
- Few details are available in the literature on the aspects of HAZ softening during SAW process. A three-dimensional analysis, aimed at predicting the microstructure in the different zones of a SAW joint, has been proposed in [6].A model to predict HAZ in case of SAW is addressed by [6] attempts to predict HAZ in case of SAW. The combined effect of flux chemical composition and of the welding parameters on the mechanical properties of SAW process has been shown to be of major importance [7-8]. Although the SAW process has drawn much of attention, in recent time [6-10], it is quite clear that a systematic study to bring out a correlation- based performance characterization through identification of control parameters in conjunction with quality assessment, is still missing.

- The identification of the contribution of each process parameter on the quality or performance of a SAW joint, poses a challenge to the researchers in this area and demands a very systematic study of the problem. Since the HAZ width is controlled by process parameters and heat input [4], an attempt was made in this paper to correlate the HAZ width with these quantities, in order to optimize the process variables for minimum HAZ width.

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 30×15×2cm. An ESAB SA1 (E8), 0.315 cm diameter, copper coated electrode and a 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 were cut and V groove of angle 60° as per the standards were prepared.
- The chemical composition of work piece material is described in Table 1. 0.1 cm 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. HAZ width has been measured with the help of optical research microscope(NEOPHOT-32).

DEVELOPMENT OF MATHEMATICAL MODEL

- Let HAZ width can be expressed as $Y=a_0+a_1V+a_2F+a_3S+a_4N+a_5V^2+a_6F^2+a_7S^2+a_8N^2+a_9VF+a_{10}VS+a_{11}VN+a_{12}FS+a_{13}FN+a_{14}SN$
- Where V, F, S and N denote Arc Voltage, Wire Feed Rate, Travel Speed and Stick Out respectively. From the data of table-2 the a_i coefficients (with i=1-14) were calculated by MAT LAB and tabulated in table-3. Calculation of Variance for testing has been made as shown in table 4. It has been found from table-4, this regression model is adequate.

TABLE-3: Regression coefficient of model

SL NO.	Coefficient	Values of Coefficient for prediction of HAZ width
1	a_0	1.04
2	a_1	0.02
3	a_2	0.15
4	a_3	-0.16
5	a_4	-0.05
6	a_5	0.04
7	a_6	0.07
8	a_7	0.08
9	a_8	-0.01
10	a_9	0.03
11	a_{10}	0.01
12	a_{11}	0.03
13	a_{12}	-0.06
14	a_{13}	0.04
15	a_{14}	0.01

PARABOLOID HEAT SOURCE:

- Heat input is the key parameter for the change of HAZ.So study on heat distribution/transient temperature distribution on welded plate is very essential. For submerged arc welding process heat distribution shape has been assumed as paraboloid.
- Let a paraboloid heat source, in which heat is distributed in a Gaussian manner throughout the heat source volume, was initially considered. The heat density q(x, y, z) at a point(x, y, z) is given by the following equation:
- $q(x, y, z) = A\, e^{-(z^4-ax^2-ay^2)}$ (1)
  Where A, a are the maximum heat density and paraboloid heat source parameter respectively.

- If Q_0 is the total heat input, from fig-1,it can be written as
- $Q_0 = \int_{-L}^{L} \int_{-B}^{B} \int_{0}^{D} q(x, y, z)$
- Or $A = C \times Q_0$ [where $C = 4(L + \frac{aL^3}{3}) \times (B + \frac{aB^3}{3}) \times (D + \frac{D^5}{3})$]

(using expansion of function theory)

- Oval shape heat distribution equation is:
- $q(x, y, z) = C \times Q_0\, e^{-(z^4 - ax^2 - ay^2)}$ (3)
- Here, $Q_0 = I \times V \times \eta$ (4)
- Being V, I and ŋ the welding voltage, the current and the arc efficiency respectively.
- Arc efficiency is taken 1for submerged arc welding process, as mentioned in [4].

INDUCED TEMPERATURE FIELD

- Heat conduction in a homogeneous solid is governed by the linear partial differential equation
- $k\nabla^2 T + q = \rho c_p \frac{\partial T}{\partial t}$ (5)
- Where T = T(x, y, z, t) is the temperature at point(x, y, z) at time t, q is the heat source,ρ is the density, c_p is the heat capacity and k is the thermal conductivity of the plates of welded plates.

- The fundamental solution of equation (5) is the Green function, i.e.
- $G\,(x\text{-}x', y\text{-}y', z\text{-}z', t\text{-}t') = \frac{1}{\rho c_p[4\alpha\pi(t-t')]^{3/2}} e^{[(-\frac{(x-x')^2 + (y-y')^2 + (z-z')^2}{4\alpha(t-t')}]}$ (6)
- Where a = k/(ρc) is the thermal diffusivity.
- Equation (6) gives the temperature increment at point(x, y, z) and at instant t due to an instantaneous unit heat source applied at point (x',y',z') at instant t', assuming the body to be infinite with an initial homogeneous temperature.

- Then, due to the linearity of equation (5), the temperature variation induced at point(x, y, z) at time t by instantaneous heat source of magnitude
- q (x',y',z',t') applied at (x',y',z') at time t' is
- q (x',y',z',t') G $(x-x', y-y', z-z', t-t')$ (7)
- Assuming that heat has been continuously generated at point (x', y', z') from t'=0, the temperature increment at point(x, y, z) at time t is
- $\int_0^t q\,(x',y',z',t')\,G\,(x-x',y-y',z-z',t-t')\,dt'$ (8)
- If we assume that the heat has been continuously generated from t'=0 throughout an infinite medium, the temperature increment at any point (x, y, z) and at any instant t takes the form
- $\Delta T(x, y, z, t) = \int_0^t . \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} q\,(x',y',z',t')\,G\,(x-x',y-y',z-z',t-t')\;dx'\;dy'\;dz'\,dt'$ (9)

- Then the temperature induced by the oval heat source defined by equation is
- $\Delta T(x, y, z, t) = \int_0^t . \frac{1}{2} \times \frac{Q_0}{\rho c_p \pi^{\frac{3}{2}} [4\pi\alpha(t-t')]^{3/2}} \times \frac{2a}{\pi^{3/2}} \times Q_0 \times I_x \times I_y \times I_z dt'$ (10)
- Finally, by assuming the body was initially at the homogeneous temperature T_0, the temperature field is defined by
- $T(x, y, z, t) - T_0 = \int_0^t . \frac{1}{2} \times \frac{Q_0}{\rho c_p \pi^{\frac{3}{2}} [4\pi\alpha(t-t')]^{3/2}} \times \frac{2a}{\pi^{3/2}} \times Q_0 \times I_x \times I_y \times I_z dt'$ (11)

- Applying expansion of function theory we get-
- $I_z = \int_{-L}^{L} e^{(-\frac{(z-z')^2}{4\alpha(t-t')})} \times [e^{-(z'^4)}]dz')$
- $=2[L-\frac{(z-L)^3}{12\alpha(t-t')} - \frac{L^5}{5}]$
- $I_y = \int_{-B}^{B} e^{(-\frac{(y-y')^2}{4\alpha(t-t')})} \times (e^{ay'^2})\, dy',$
- $=2[B-\frac{(z-B)^3}{12\alpha(t-t')} + \frac{B^3}{3}]$
- $I_x = \int_{0}^{D} e^{(-\frac{(x-x')^2}{4\alpha(t-t')})} \times [e^{(ax'^2)}\, dx'$
- $= [D-\frac{(x-D)^3}{12\alpha(t-t')} + \frac{D^3}{3} + \frac{(D)^3}{12\alpha(t-t')} - 1]$

Prediction of HAZ width

- HAZ width of a C-Mn steel is the region heated from lower critical temperature (i.e., 723℃) to the temperature just below the melting point temperature of welded materials (i.e. 1464℃). Putting these values in the equation (11) HAZ width(s) can be calculated at z=0, $x=vt'$, (where, v=30cm/min), $t=t'$ = travel time=60 sec, of electrode. Comparison between computed and experimental data for HAZ width which is described in figure-2

OPTIMIZATION OF HAZ WIDTH

- HAZ width is a function of the process parameters of SAW process and these, in turns, depend on the heat input as heat input is the function of voltage, travel speed, wire feed rate, stick out etc. By taking values of HAZ width and heat input from table-2, a relationship between the heat input and HAZ width was find out through regression model, in the form :
- $y=1.4901x-0.3377x^2+0.0207x^3$, where y=HAZ width and x=heat input .The optimum value of the HAZ width (0.9 mm when heat input =7.76kJ/cm) was obtained from figure 3.

CONCLUSION

- A good agreement between the predicted and measured values of HAZ width has been achieved by ignoring convective and radiative heat lost by the welded plate. The considered heat source shape for submerged arc welding in this analysis was a paraboloid. The optimum setting of input variables has been found in order to minimize the HAZ width.

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

C	Sn	Mn	P	S	Cr	Ni	Mo	Cu	Al
0.18	0.36	1.58	0.023	0.027	0.06	0.03	0.01	0.04	0.05

Table-2: Observed values of HAZ width

Sl.No.	Arc Voltage (volts)	Wire Feed Rate (m/min)	Travel Speed (m/min)	Stick Out (mm)	Heat Input (kJ/cm)	HAZ width (mm)
1	27	1.0	0.6	33	8.1	1.32
2	31	1.0	0.6	33	9.3	1.29
3	27	1.5	0.6	33	8.1	1.65
4	31	1.5	0.6	33	9.3	1.60
5	27	1.0	0.7	33	6.9	1.10
6	31	1.0	0.7	33	8.0	1.15
7	27	1.5	0.7	33	6.9	1.20
8	31	1.5	0.7	33	8.0	1.15
9	27	1.0	0.6	38	8.1	1.14
10	31	1.0	0.6	38	9.3	1.13
11	27	1.5	0.6	38	8.1	1.38
12	31	1.5	0.6	38	9.3	1.70
13	27	1.0	0.7	38	6.9	1.00
14	31	1.0	0.7	38	8.0	0.90
15	27	1.5	0.7	38	6.9	1.00

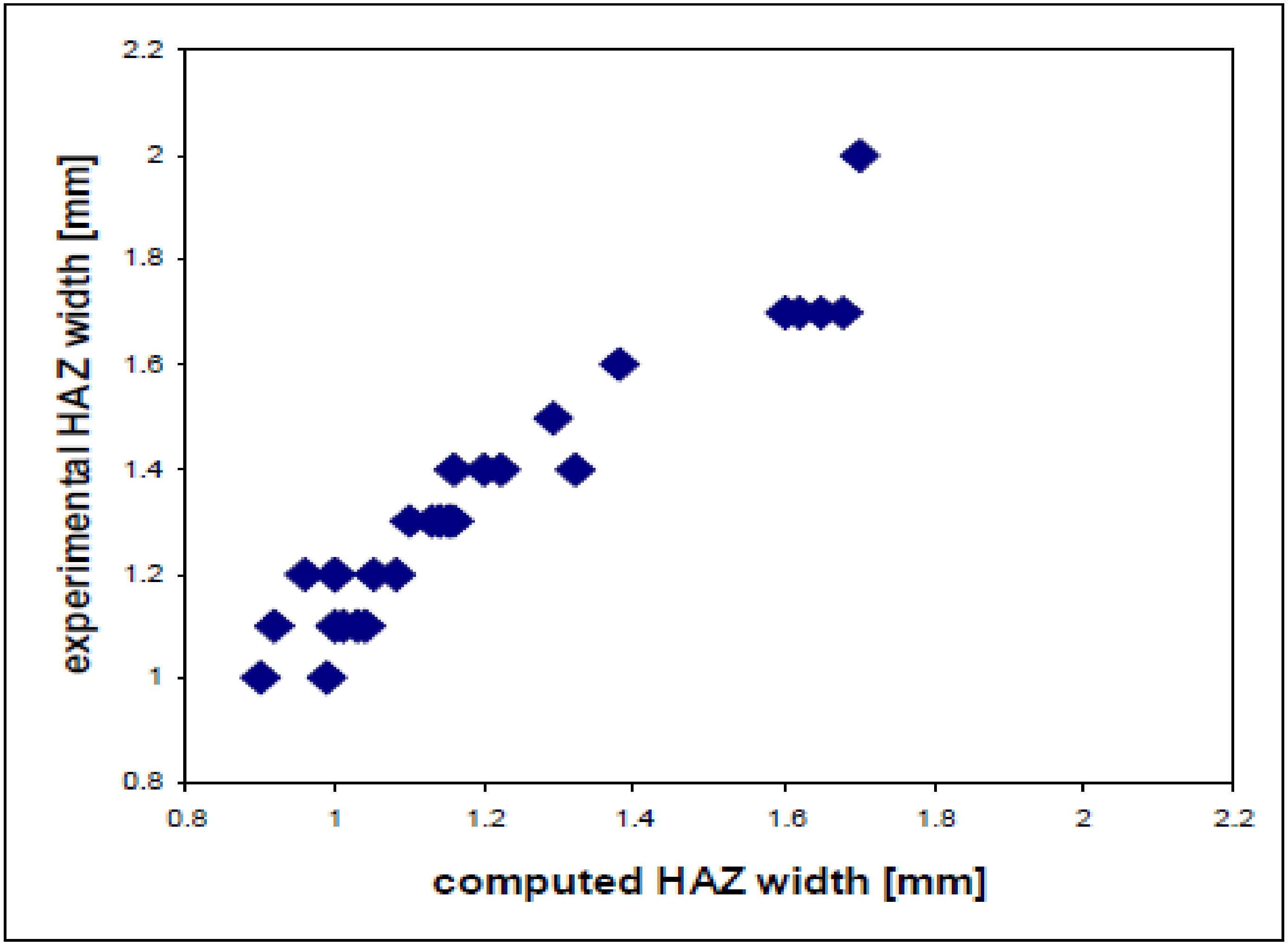

Figure-2: Comparison between computed and Experimental data

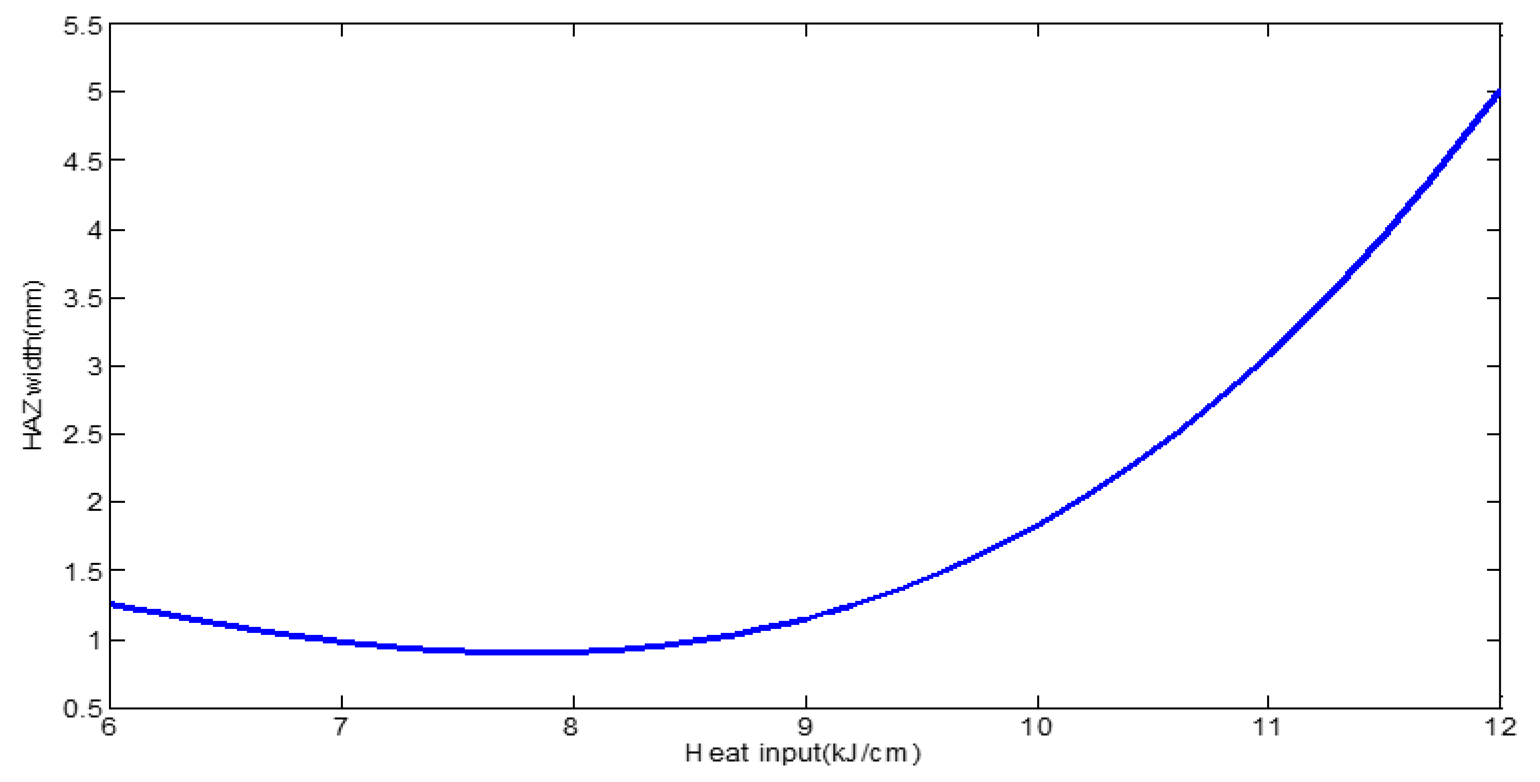

Figure 3: Graphical representation between heat input and HAZ width

Table-4: Calculation of Variance for testing the adequacy of the model

BEAD PARAMETER	FIRST ORDER TERM		SECOND ORDER TERM		LACK OF FIT		ERROR TERM				WHETHER MODEL IS ADEQUATE
	SS	DF	SS	DF	SS	DF	SS	DF	F RATIO	R RATIO	
HAZ width	1.18	4	0.4	10	0.08	10	0.03	6	1.9	5	ADEQUATE

Here SS –sum of square, DF-degree of freedom

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