HEAT TRANSFER IN WELDING - A NUMERICAL APPROACH

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The effectiveness and profitability of welding operation depends upon the efficiency of each individual phases of the process namely, joint configuration, welding parameters, quality of weldments and subsequent repair of defective welds. Out of the four phases, welding process parameters and quality control are the foremost areas where evaluation of data is carried out extensively. These data in turn are used for the selection of the most suitable process of welding along with its parameters, for a particular use. The thermal based problems, e.g. transient heat transfer in weld and base metal, transient thermal stress and strains, transient metal movement during distortion, residual stresses and distortion after welding, etc. may easily be solved by numerical techniques employing computer facilities. This paper first describes the different numerical techniques generally employed in solving these welding problems along with their suitability and applicability. Later, it elaborates a generalised approach of numerical technique for predicting temperature histories in a weld cross section and associated cooling rates. The validity of the model was ascertained through experiments carried out on indigeneously produced HSLA steel plates employing submerged arc and carbon-di- oxide welding process. A comperative study with Rosenthal equation confirms a better match of the numerical technique with the experimental values. The cooling rate information thus obtained may then be used to assess the related microstructure and mechanical property changes for a particular steel.

q(r,t) = Heat flux on the surface of weldment, **q (x,y,z)** = is the power density with moving coordinate (x,y,z) of a reference point, **q** = prescribed heat flux at the boundary, **r** = Characterstic that defines the region in which 95% of heat is deposited., **h** = Heat transfer coefficient., **t** = Time., c_p = specific heat of the weld material., **Kx,y,z** = Thermal conductivity of the weld material., **K1** = Constant., **K2** = Constant., **KaT/an** = Heat flux in the normalized direction.., **Q** = Heat input., **S** = The number of dimention in the analysis., **ST** = Surface of the domain where specific temperature is prescribed., **Sq** = Surface of the domain where specific heat flux is applied., **Sh** = Surface of the domain where there is heat transfer to surrounding., **T** = Temperature of interest., **To** = Initial temperature of plate., **TS** = Specific temperature at the surface., **T1** = Temperature/peak temperature where cooling rate is to be found., **T1,j** = Temperature of a nodal point (i, j)., **Te** = Temperature of an element (finite element technique)., **V** = Welding speed., **W** = Thickness of the plate., **at** = Time interval., **DX** = space increment ., **a** = Thermal diffusivity ., **o** = Fourier number ., **R** = Radial distance.

INTRODUCTION

The thermal based problems e.g. transient heat transfer in weld and base metal, transient metal movement during distortion, residual stresses and distortion after welding are of major concern in a welding industry. These thermal problems are the outcome of the application of a localized intense heat input from the welding arc. Accurate predictions of distortion, residual stresses, related microstructural and mechanical property changes, etc., require a meticulous estimation of temperature distribution in the weldment for a particular welding process. Plate dimension, thick or thin, affects heat transfer analysis and subsequent cooling rate calculations (1-4). Literature survey reveals an arbitrariness in specifying this thickness parameter. To remove this discrepancy an unique way of thickness determination has been suggested which is of great practical importance too. Position of heat affected zone, which can be calculated theoretically (5), within the thickness of the plate has been used as the criterion for this purpose. Only after thus specifying the thickness of a plate the different numerical techniques may be applied for finding the thermal profile and cooling rates. The relative merits, demerits, application criterion, etc. for these too commonly employed numerical techniques have been detailed in Table 1.

A generalised approach to a heat transfer model for accurate determination of thermal history has been put forward in this paper. This is of immense significance in understanding the heat transfer aspects of a weldment and helps in ascertaining various remedial measures, e.g. fixing the most suitable welding parameters, choosing proper preheat temperature etc, to yield a defect free weld. The validity of this model was first ascertained through experimental work. Later, a comparative study with the analytical approach namely the Rosenthal equation was also carried out.

Theoritical Considerations

The proposed generalised model for calculating the thermal profile and cooling rate has been presented in Fig. 1. The various steps involved in this model has been detailed as under :

Input data : The input data required for such analysis may be divided into the following

i) Geometry of the joint e.g. bead on plate, grooved butt joints, fillet joints, etc.

ii) Modes of heat input e.g. normal, weaving, pulse or arc spot.

iii) Material properties e.g. conductivity, latent heat of fusion, heat capacity, melting point etc.

iv) Welding parameters e,g, thermal efficiency, arc current, arc voltage and welding speed etc.

Heat source model ; The geometry and location of melting zone in a weldment are greatly influenced by the distribution of heat from the arc to the weldment surface. For a welding situation, where the effective depth of penetration is small, the surface heat source model as suggested by Friedman(11) is found suitable. The heat distribution on the surface at time, t, and at a distance r is then given by

$$q(r,t)=\frac{3Q}{\pi \bar{r}^2}\,\mathrm{Exp}[-3(r/\bar{r})^2]\;\mathrm{Exp}[-3(\cdot t/\bar{r})^2] \qquad (1)$$

However, for high power density sources such as of laser and electron beam, where the depth of penetration is large, a more realistic hemispherical Gaussian model of power distribution(8) is more suitable. The power density distribution for a hemispherical volume source is then written aσ

$$q(x,y,\xi)=\frac{6\sqrt{3}Q}{\pi \bar{r}^2\sqrt{\pi}}\,e^{-3x^2/\bar{r}^2}\,e^{-3y^2/\bar{r}^2}\,e^{-3\xi^2/\bar{r}^2} \qquad (2)$$

Heat flow equation : The temperature, T(x,y,z,t), as a function of space and time (t), at actual welding condition can be found from the following parabolic heat transfer equation

$$\partial/\partial x\, K_x\, \partial T/\partial x + \partial/\partial y\, k_y\, \partial T/\partial y + \partial/\partial z\, k_z\, \partial T/\partial z + Q = pcp\, \partial T/\partial t \qquad (3)$$

subjected with conditions

*$T = T_s$ on part of boundary S_T

*$K_n\, \partial t / \partial n = q$ on part of boundary S_q

* $K_n\, \partial T/\partial n = h(T-T_0)$ on part of boundary S_h and

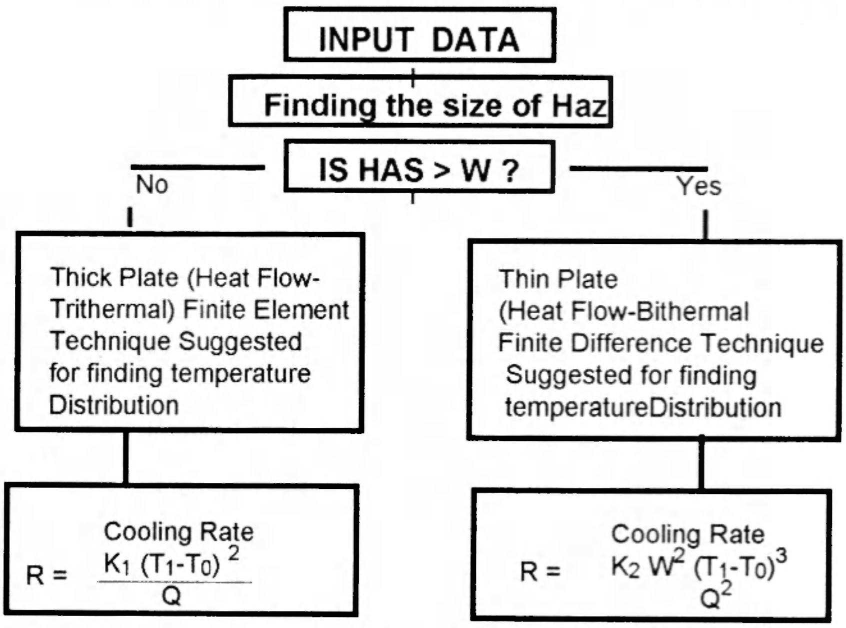
* The initial condition $T(x,y,z,o) = T_o(x,y,z)$

If the partial differential equation, the initial condition and the boundary conditions are consistent the problem can be solved numerically.

Thickness designation : The specification of thick plate and thin plate in heat transfer study is based upon the following considerations. If the plate is thin, the bottom surface should be essentially at the same temperature as of the top surface. However, if the plate is thick, the bottom surface is unlikely to be as hot as the top. In the later case the plate itself will be acting as a heat sink, causing the heat to flow through the thickness of the plate to-

Table 1 : Comperative Study of Nemerical Techniques for thermal Problems in Welding

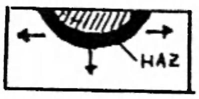
Finite difference	Finite element
Approach: General finite difference technique with appropriate condition is used to find temperature distribution in thin plates during welding	General finite element technique is used for sorting thermal problems during welding. Mostly applied for higher number of unknowns.
Advantage : i) Easy to model regular and simple geometry, ii) Computer implementation for the problem is easy, iii) Easy for predicting temperature distribution	i) Ability to model the most complex and arbitrary geometries, ii) Ease of transition from heat transfer to thermal stress and other types of solution iii) Ability to easily accommodate complex condition such as intimate contact change in physical properties.
Difficulties : i) Difficult to model very complex and arbitrary geometries ii) Subsequent analysis for stress, distortion etc. is very difficult.	i) Computer implementation is cumbersome and requires more memory.
Practical/Industrial applicability. i) Used for solving the thermal based problems.	i) Widely used for all sorts of numerical analysis of thermal based problems.
Previous Research :	
i) Simulation of heat flow during the welding of thin plate(1), ii) Rapid melting and solidification of surface due to moving heat flow(6), iii) Computation of temperature in thin tantalum sheet welding(2), iv) Computation of temperature in actual weld design(4), (v) Ecperimental and computed temperature histories in gas tungsten arc welding of thin plates(3).	i) Computer modelling of heat flow in welds(7), ii) A new finite element model for welding heat sources(8), iii) Computer simulation of thermal stress and metal movement during welding(9), iv) on the calculation of temperature due to arc welding(10).



Flow chart of the generalized approach for estimating temperature distribution and cooling rate wards the bottom surface and also in the transverse direction. In thin plate, the heat flow is said to be bithermal and in thick plate, it is trithermal, as illustrated in Fig.2.

Thin plate Bi-thermal

Back surface as hot as top surface



Thick Plate Tri - Thermal

Back surface does not heat up

Fig : 2

A weakness of the thin plate and thick plate approach to the heat transfer analysis is that one does not know which plate is thin enough for considering heat flow is bithermal or which plate is thick enough for trithermal heat flow consideration.

The authors feel that the size of heat affected zone in the cross section may be the guideline for distinguishing the thin plate from thick plate for particualr heat input. If the HAZ due to a particular heat input, gets truncated with the actual thickness of the plate then the plate is specified as THIN and if the HAZ is lying within the thickness the plate is THICK as clearly shown in Fig.2. So the determination of the size of HAZ and its position with respect to thickness are prerequisite for the present efficient modelling of heat transfer aspect.

A previous work of the authors (5) details guidelines for preficting the size of the HAZ, which can be used to designate the specification of thin plate of thick plate.

Numerical solutions : The two most commonly applied numerical techniques have been discussed in the following paragraphs.

i) Finite difference : The transformation of the main hjeat transfer equation 3 by an explicit finite difference method (two dimensional) will lead to the following nodal equation for equal increment in X and Y direction for a particualr node

$$T_{i,j}^{n+1} = T_{i,j}^{n} + \phi\left[T_{i+1,j}^{n} + T_{i-1,j}^{n} + T_{i,j-1}^{n} + T_{i,j+1}^{n} - 4T_{i,j}^{n} + q/Kw\right] \quad (4)$$

where T^{n+1}_{ij} and $T^{n}_{i,j}$ are the nodal temperature at time, $t+\Delta t$, and t, respectively.

$\varnothing = \alpha \Delta t / \Delta x^2$

$\alpha = K/\rho c_p$ and Δx is the node spacing

The time step in the explicit finite difference analysis is limited by

$$\Delta t \leq \frac{\Delta X^2}{2\alpha S}$$

The contribution of weld pool convection is incorporated into the computations by multiplying the conductivity of the liquid by a factor ranging from 3 to 10. Single values of physical properties may be taken near the melting point of the alloy for computation (2). Such considerations give accurate results of temperature distribution near the weld pool vicinity which is the zone of interest for the thermal analysis.

ii) Finite element : Finite element formulation for transient heat flow, in case of welding, may also be derived from the main heat flow equation :

The unknown temperature, T, within each element may be represented as

$$T^{(e)}(x,y,t) = \Sigma^{n}_{1} Ni(x,y)\, Ti(t) = [N]\,[T]^{e}$$

where $[N]=[N_1, N_2, N_i \ldots\ldots N_n]$ and, N_i, N_j etc. are the shape functions defined piecewise, element by element and in the summation , the appropriate functions for the particualr point must be used. $T_i, T_j \ldots$ etc. are the values of the temperature $T^{(e)}$ at various nodes i,j of the element. The $T^{(e)}$ values obtained from the above equation when substituted to eqn. 3 would give equation for n values of $T^{(e)}$. To minimize the weighted and integrated residuals, these n-sets of equations may then be equated to zero, leading to the following general equation

$$H + T + Q = 0 \quad (5)$$

in which, thermal stiffness conductivity H is given by

$$H_{i,j} = \Sigma \int_e \left(K_x \frac{\partial N_i}{\partial x} \frac{\partial N_j}{\partial x} + K_y \frac{\partial N_i}{\partial y} \frac{\partial N_j}{\partial y} + \rho c_p N_i \frac{\partial N_i}{\partial t} \right) \partial x\, \partial y\, \partial t + \Sigma \int_s N_i h N_j\, ds$$

and thermal heat vector Q is

$$Q_i = -\Sigma \int_e N_i Q\, dx \cdot \partial y \cdot dt + \Sigma \int_{s} N_i q \cdot ds - \Sigma \int_s N_i h T_o\, ds$$

These sets of equations are then used for calculating new sets of temperature at particular time, if the initial temperature is known. Similarly, at each new time-step an identical procedure may be used until a prescribed time is reached. The time- temperature values thus obtained ultimately materialises the temperature distribution.

Cooling rate : The concept of bithermal and trithermal heat flow in welding leads to the following cooling rate formulations for thick plate and thin plate (12)

Thick plate : $$R = \frac{K1\,(T1 - To)2}{Q}$$

Thin Plate $$R = \frac{K_2 W^2 (T_1 - T_o)^3}{Q^2}$$

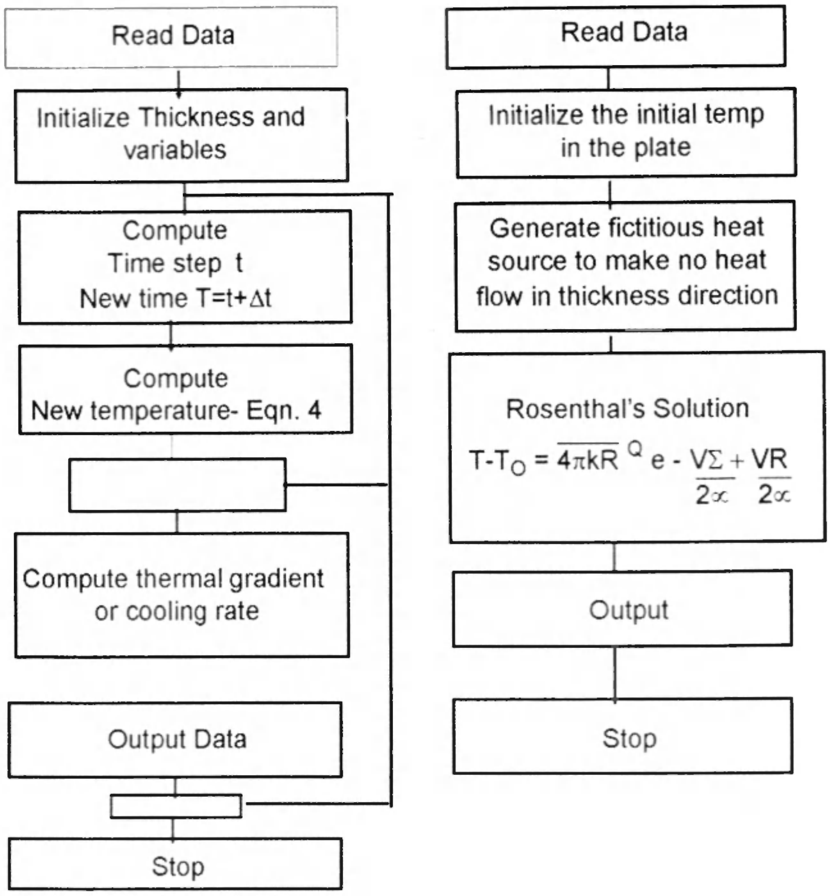
The cooling rate at a particular instant is directly related to the peak temperature at a point in the weldment at a particular time.

Experimental Work

To check the validity of this generalised approach of heat transfer analysis, experiments were carried out on indigenously produced H.S.L.A. steel plates of chemical composition as in Table 2. The thermal profiles of these plates were experimentally obtained employing CO_2 and submerged arc welding processes. The details of the experimental procedure is discussed elsewhere (5). With the aid of thermocouples connected to various recording units, it is possible to record the heating curve, peak temperature and the cooling curve of any point of interest in the plate.

Result And Discussion

The Fig. 3 shows the flow chart of the numerical technique (finite difference) and analytical solution to predict the thermal profile to check the validity of the general approach of a nemerical technique for heat transfer in a welding process. The calculated value of HAZ was first specified to ascertain if the experimental plate was thick or thin. Fig.4 shows the thermal profiles obtained through experiment, analytical solution and present numerical analysis (solved by iterative method by ICI. 370 digital computer) for a particular point. Similar plots were obtained at several points in the plate for checking the consistency of the results.



Simplified flow diagram for finite difference analysis of temperature distribution during welding

Flow diagram for analytical solution of temperature distribution during welding.

Fig 3

However the validity of the Finite element model to be applied to thicker plate are being carried out presently in the Department of Matallurgical Engineering B.H.U. From the result as in Fig. 4 it is clear that

Table 2 : Properties and Chemical Composition of the Low Alloy Steel

	Symbol	Value
Solidus temperature.	°C	1443
Liquidus temperature	oC	1468
Density	Pg mm^{-3}	0 007833
Thermal conductibity	K.Cal/sec °C.mm	0.01250
Heat capacity(solid).	C_p Cal/gm °C	0.1427
Heat capacity(liquid)	C_p Cal/gm °C	0.1427
Thermal diffusivity	$\propto m^2$/sec	11.11
Chemical composition		
Carbon 0.1 Max		
Manganese 0.35		
Sulphur 0.04		
Silicon 0.04		

i) The thermal profile calculated by explicit finite difference method closely matches with the experimental one. The experimental curve was somewhat depressed and it may be due to the slow response of the thermocouple to sudden changes in temperature during welding.

ii) The analytical result does not match with the experimental measurements. The reason might be that the thermal conductivity of carbon steel can be three times lower at melting temperature than at room temperature.

Assumption of constant thermal properties causes the discrepancy in both magnitude and gradient of the thermal profile depending upon the values used. The concentrated heat source model has a singularity at the source. So the calculated temperature by analytical equation becomes infinitely high at the source and low in the area away from the source.

It may be inferred that the present numerical approach is very suitable for predicting the temperature distribution for any type of plate. Once these thermal profiles and cooling rates arc calculated at any instant, these data in turn may easily be used for predicting the microstructure through the use of CCT diagram (5), residual stresses and metal movement (9) etc. Thus the importance of accurate prediction of thermal profile of a weldment is clearly understood.

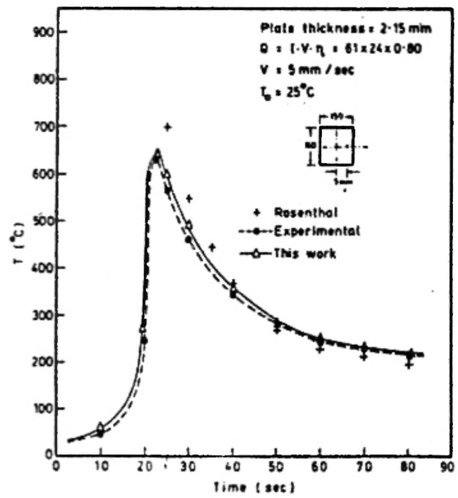


Fig. 4. : Time - temperature profile for a point in the weldment.

CONCLUSION

While using the proposed heat transfer model based on numerical approach.

i) An accurate temperature distribution may be obtained for any plate employing any welding process.

ii) A more realistic view of thick plate and thin plate specification for heat transfer analysis is possible. The thickness parameter is rendered independent of welding process and welding parameters and instead it is made a variable with respect to the HAZ created.

iii) The calculated cooling rates may be used for estimating the microstructure, residual stresses etc.

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