3-D FINITE ELEMENT ANALYSIS ON HEAT FLOW IN WELDING UNDER VARYING ARC LENGTHS

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Abstract : *Arc length is an important variable affecting the heat flow in welding. In the present paper a three dimensional transient finite element analysis on heat flow in arc welding under varying arc length conditions have been presented. The problem was solved by considering the important factors that influence the heat transfer in arc welding, like temperature dependent material properties, enthalpy and stirring effect in molten pool. To reduce the computational time, finer mesh was generated where temperature gradient was too high and gradually mesh size was increased away from the heat source. Temperature distribution in the plate and variations of temperature along the cross-section at two positions of the arc for three arc radii were plotted for comparison.*

Keywords : *Heat flow, FE analysis, Arc welding, Arc radius. 1.0*

INTRODUCTION

Welding has been known to mankind as a method of joining materials since time immemorial. But joining by welding is associated with some problems such as those resulting from heat transfer into the work piece causing physico-metallurgical changes in the welded structure. In the past, many such problems have been tackled through experimental investigations, and trial and error methods, requiring collection of extensive data. Cost involved in the collection of data is very high and this is also not very convenient to scientific analysis. Fortunately with the advent of computers, scientific analysis and modeling can now be done more easily and readily.

In the case of arc welding, the electrode and the base material are heated above their melting points and allowed to cool to the room temperature after welding. Due to the temperature differences in the various portions of the heat affected zone of the base metal and different cooling rates, metal transforms to have different microstructures and develops residual stresses. It has thus been well established that microstructures, residual stresses and mechanical properties of the weldment depend on the temperature distribution and cooling rate of the heat affected zone [1-4].

The study of heat flow in welding has a long history. Rosenthal (1941, 1946) was the first to give the closed analytical solution of classical heat conduction equation [5-6]. Rosenthal made several assumptions to simplify the problem to determine analytically the temperature distribution and cooling rates in welding. Due to these assumptions Rosenthal's analysis is subject to serious error for predicting the temperature distribution in or near the fusion and heat affected zones at high temperatures. After Rosenthal, several researchers worked in the same direction to improve the analytical solution with limited reliability due to the complexity involved.

It is known that the physical properties of metals are temperature dependent. During the welding process, phase change also takes place. Heat is dissipated by all the three modes. The distribution of heat flux in the arc is not uniform. Thus the practical welding process is a complex one to be represented analytically. Hence many researchers tried numerical methods such as finite element, finite difference and boundary element to get approximate but close-to-actual solutions. In order to avoid the singularity in the heat capacity at the liquid-solid phase transformation, some researchers [7-9] adopted the enthalpy concept. Convection inside the molten pool was modeled by adopting enhanced values of thermal conductivity of molten material [8, 10]. Using large value of thermal conductivity at temperatures exceeding the melting point [11 -12], the stirring effect in the molten pool was simulated. The distribution of heat flux in the arc can be considered to be distributed as the Gaussian function. Moreover, in the finite element analysis, the accuracy and efficiency of the solution depend strongly on the adaptation scheme that permits mesh refinement only in the required region [13-14].

Most of the researchers have analyzed the two dimensional model of heat transfer in welding. Three-dimensional thermal analysis is very limited [15]. Arc length and hence arc radius plays a significant role in the process including the temperature distribution inside the molten pool and the metallurgical changes in the weldment. In the present work the effect of arc radius on three-dimensional temperature distribution was modeled by using the finite element analysis.

List of symbols used

G = Rate of heat generation per unit volume, W/m^3s

K = Thermal conductivity, W/m K

K_x, K_y, K_z = Thermal conductivity in x, y, z directions, W/m K

Q = Arc power, W

S = Surface

T = Temperature, °C

T_∞ = Temperature of the surrounding, °C

V = Volume, m^3

c = Specific heat, J/Kg K

h = Convective heat transfer coefficient, W/m^2 K

l_x, l_y, l_z = Direction cosines of outward normal to the boundary

q = Heat flux, W/m^2

t = Time, s

x, y, z = Coordinates

v = Arc travel speed, m/s

ρ = density of the base metal, Kg/m^3

η = Heat efficiency of the arc

Thermal model

To solve the three- dimensional finite element problem, the following assumptions have been made :

1. All the thermal properties are considered as functions of temperature. It is, however, assumed that due to thermal expansion, density and element shape are not affected.
2. To avoid the sharp changes in the heat capacity due to melting, enthalpy is assumed to be a function of temperature [16].
3. On the boundary, linear Newtonian convective cooling is assumed. No forced convection is considered [12-13,17].
4. Since radiation losses are small, they are neglected [14].
5. Heat source is assumed to have the Gaussian distribution of heat flux on the surface of work piece [2,13-14,18].
6. The stirrer effect in the molten pool was simulated by using large value of thermal conductivity for temperatures exceeding the melting point [11-12]. The temperature field in molten metal is thus governed by the same equation as is applied to the solid metal [9,11].

The governing differential equation for heat conduction in a solid is given by :

$$(\delta/\delta x)\ \{k_x(\delta T/\delta x)\} + (\delta/\delta y)\ \{K_y(\delta T/\delta y)\} + (\delta/\delta z)\ \{K_z(\delta T/\delta z)\} + G = \rho c(\delta T/\delta t) \quad ...(1)$$

Boundary and initial conditions are:

$$\text{At } t = 0,\ T = T_\infty \quad ...(2)$$

$$\text{At } t > 0, \text{ on surface S : } - K_x\ (\delta T/\delta x)\ l_x - K_y\ (\delta T/\delta y)\ l_y - K_z\ (\delta T/\delta z)\ l_z = h\ (T - T_\infty) \quad ...(3)$$

The functional formulation equivalent to Equ.(1) with its boundary conditions given in Equs(2) and (3) is given as [6] :

$$\chi = \int_v (1/2) [K_x (\delta T/\delta x)^2 + K_y (\delta T/\delta y)^2 + K_z (\delta T/\delta z)^2 - 2 \{G - \rho c (\delta T/\delta t)\} T] dV + \int_s [(1/2) h(T - T_\infty)^2] dS \quad ...(4)$$

The final system of equations can be written as :

$$[C] (\delta\{T\}/\delta t) + [K] \{T\} + \{F\} = 0 \quad ...(5)$$

Fig. 1 shows the variation of thermal conductivity with temperature [9]. The curve was rounded off to avoid sharp variation. Enhanced values (8% increment at 1500°C) of K were extrapolated at higher temperatures to compensate for the stirrer effect in the molten pool. Values of enthalpy were calculated from the values of heat capacity reported in reference [9] and plotted in Fig. 2 with suitable adjustment wherever necessary. Temperature dependence of the convective heat transfer coefficient is shown in Fig. 3.

Transient heat flow analysis due to moving arc

Fig. 4 shows the plates to be welded by arc welding. Heat transfer from the welding arc at any time on the surface of the work piece, was assumed to be radially symmetric normal distribution function [20]. Let r be the distance from the weld line in the section at x = 0 and t = 0, the time at which the centre of the heat source, that is the electrode, passes over this section. Then the heat flux distribution on the surface of the weldment is given by :

$$q (r,t) = 3\eta Q/(\pi r^2) \exp[-3(r / r)^2] \exp[-3(Vt / r)^2]$$

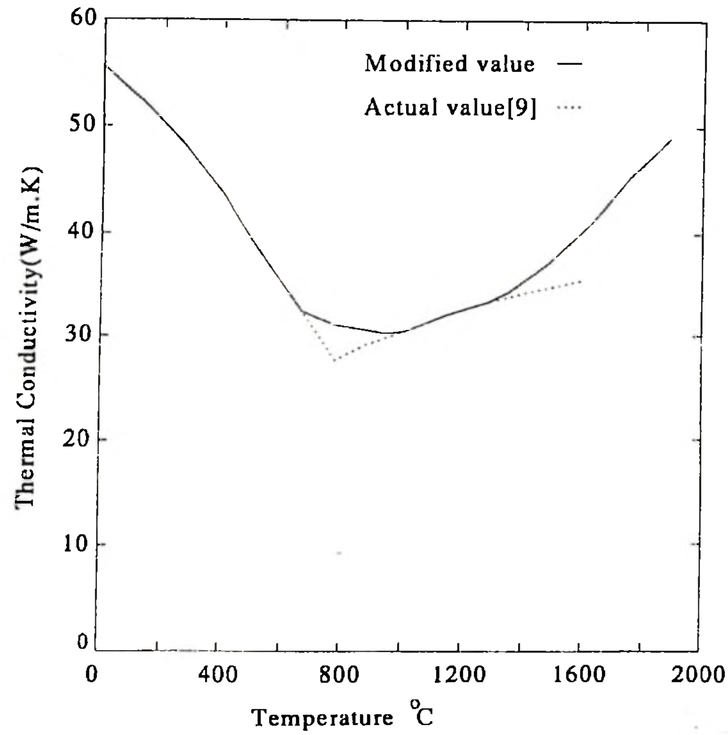


Fig. 1 : Thermal Conductivity of mild steel St 37

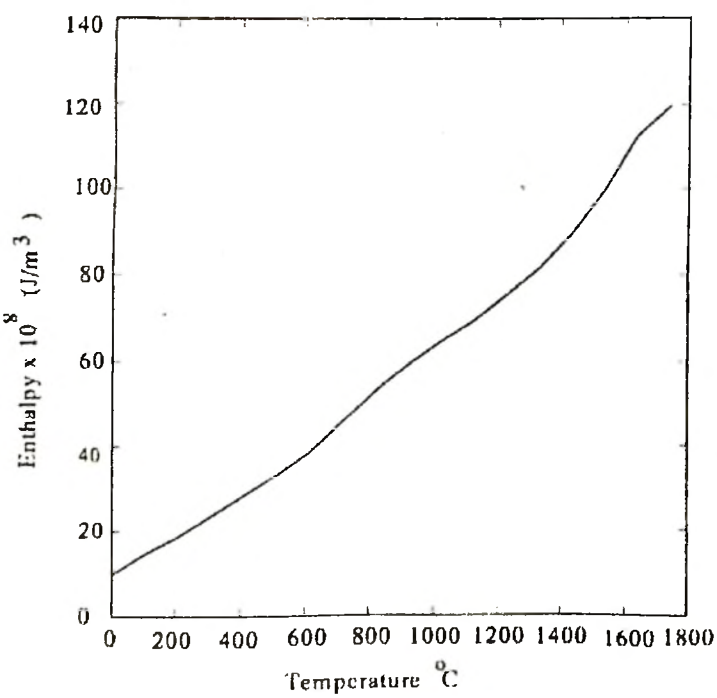


Fig. 2 : Enthalpy of mild steel St 37

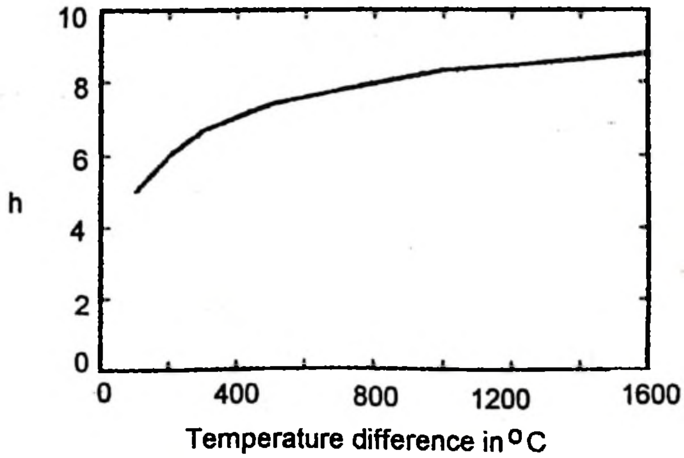


Fig. 3 : Convective heat transfer coefficient [9]

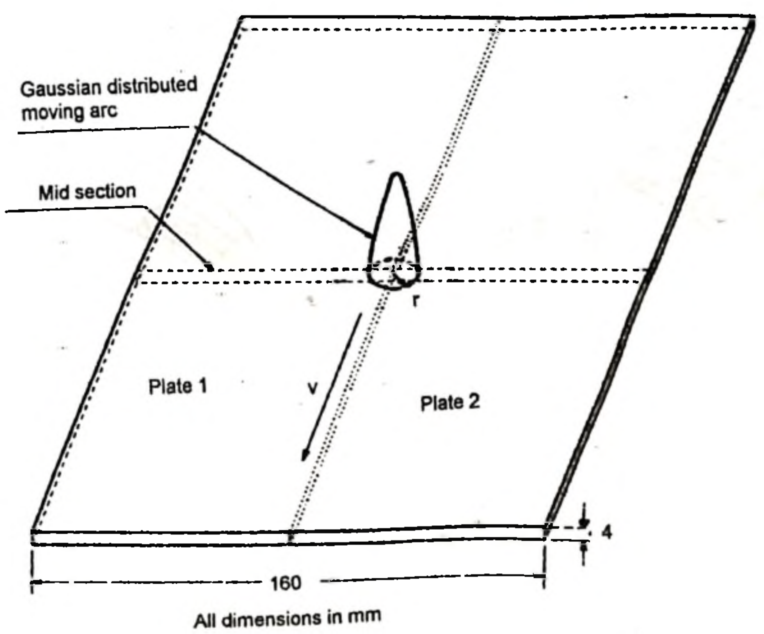


Fig. 4 : Arc welding of steel plate

where, r defines the region in which 95% of heat flux is deposited.

The above model was tested and compared [21] with the known experimental and calculated results reported in the literature [9,14]. In the present paper transient heat flow analysis was carried out for an average welding speed of 3.33 mm/s and heat flow rate of 1680 W. The problem was solved with the help of ANSYS 5.0 package. The room temperature was taken equal to 25 °C. To improve the accuracy of the result, element size was kept smaller around the heat source where the temperature gradient was too high and it was gradually increased away from the heat source which was moved from one end of the work piece to the other end. The temperature distribution was plotted for various positions. Figs. 5 and 6 show the type of meshing and temperature distribution at 18.018 seconds for arc radius of 9mm. The same at 25.518 second is shown in Figs. 7 and 8.

Results and Discussions

Temperature distributions at mid section at the time of passing arc (Fig. 9) and 7.5s after passing the arc (Fig. 10) have been compared for three arc radii (6, 9 and 12mm). From Fig. 9 it can be seen that the temperature of the metal at the centre of the arc increases with decreasing arc radius. This is obviously due to the increase in the heat flux at lower arc radius. At very large arc lengths the temperature may be too small to melt the metal. From this analysis. the temperature in the molten pool can be predicted and thus the arc length can be controlled. Fig. 10 compares ths temperature distribution in the transverse direction for three arc radii at the mid section after 7.5s of passing the arc. The trend is same as in the earlier case.

Conclusions

Three-dimensional heat flow in welding under varying arc length condition has been successfully modeled and analyzed by finite element method. The results show

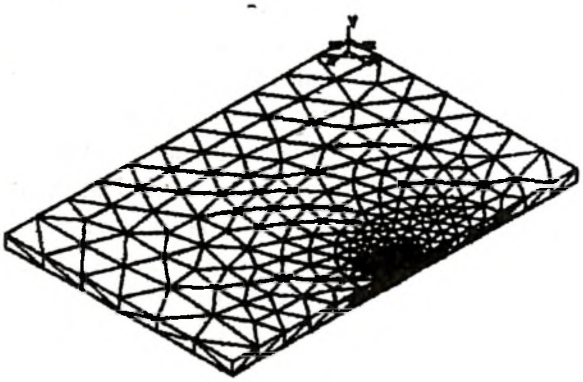
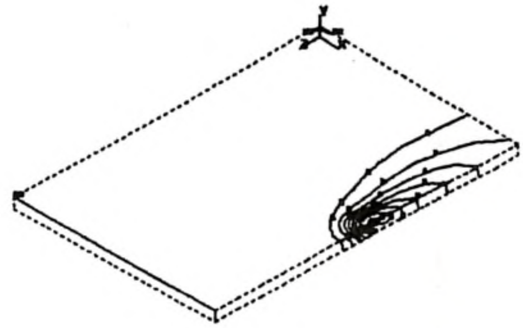


Plate size 120 mm x 80 mm x 4 mm

Fig. 5 : Type of mesh at mid position of arc for arc radius 9 mm



Temperature in ^{o}C

A = 225, B = 450, C = 675, D = 900, E = 1125

F = 1350, G = 1575, H = 1800

Fig. 6 : Temperature distribution at 18.018 s (mid section) for arc radius 9 mm

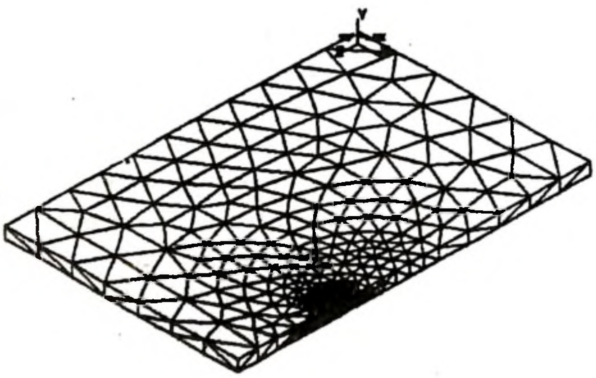
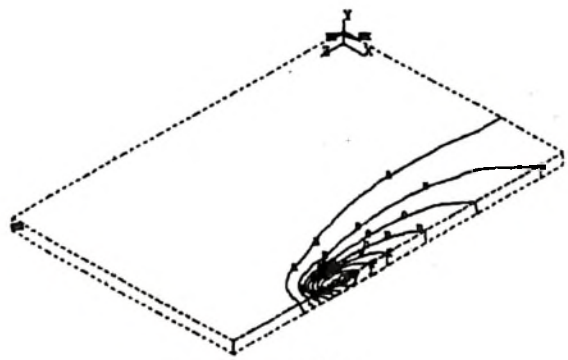


Plate size 120 mm x 80 mm x 4 mm

Fig. 7 : Type of mesh at 25.518 s for arc radius 9 mm



Temperature in ^{o}C

A = 225, B = 450, C = 675, D = 900, E = 1125

F= 1350, G = 1575, H = 1800

Fig. 8 : Temperature distribution at 25.518 s for arc radius 9 mm

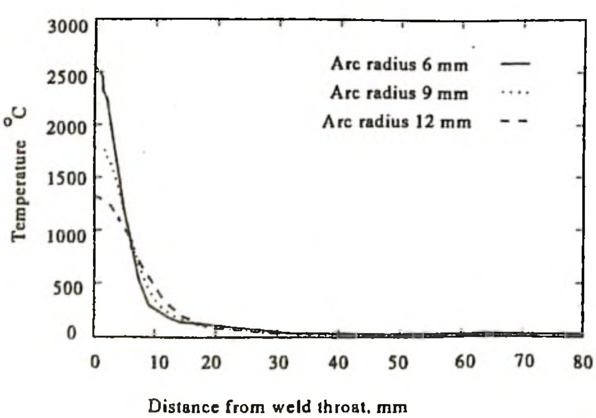


Fig. 9 : Transverse temperature distribution at mid section during passing arc

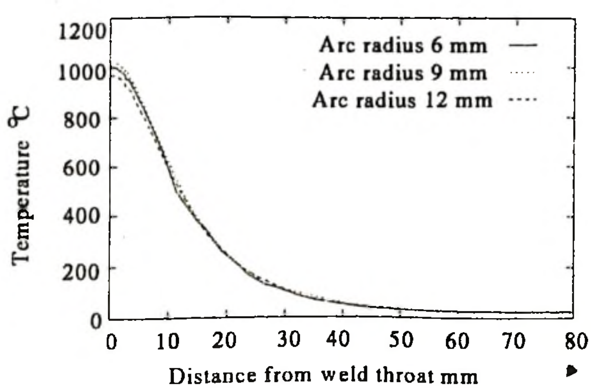


Fig. 10 : Transverse temperature distribution at mid section 7.5 s after passing arc

that the arc length has a significant effect on the temperature of the molten pool and that of the adjacent base metal.

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