ONE DIMENSIONAL HEAT FLOW IN ARC WELDING ELECTRODES

Dr. N. K. Batra

Professor, Dept. of Materials and Metallurgical Engg.
Indian Institute of Technology, Kanpur 208016.

INTRODUCTION

Arc welding processes such as Shielded Metal Arc Welding, Gas Metal Arc Welding. Submerged Arc Welding, Flux Core Arc Welding and Electro Gas Welding dominate the present day world scenario in bulk joining of metals. The current rating of the electrodes used in these welding processes may be governed by the heat flow considerations. For example, melting rate of the electrode is attributed to the following factors :

A. Heat is produced due to finite voltage drop occurring in a region of less than 0.1 mm near the tip of the electrode when current is passed to sustain the arc.

B. The electrode is resistance heated due to flow of the current.

Combining the two factors, the following expression describes the melting rate of the electrode material[1,2]

$$M_R = \alpha I + 4\beta I^2 L\, \rho_e / \pi d^2 \quad ....1$$

M_R is melting rate, α and β are constants of the process, ρ_e the electrical resistivity of the material, L extension length and d diameter of the electrode. The extension length of the electrode is the distance between the point of electrical contact and the tip of the electrode. For the shielded metal arc welding using covered electrodes, the extension length equals the length of the electrode at any instant. For processes such as gas metal arc welding, the extension length remains more or less constant. Typical value of α for shielded metal electrodes lies in the range of 0.009 to 0.012 kg/h/ampere. Second term in equation(1) may be ignored for the covered electrodes because of the lower current range in which they are mostly operated. For submerged arc welding, thermal efficiency of the process is high and value of α may be close to 0.02. For gas metal arc welding and flux core arc welding of steel, α may be close to 0.01. The value of β ρ_e product for steel wire is close to 1.17 x 10^{-9} kg m/h/ampere^2. Feed rate of the electrode wire must match the rate at which it is melted away at the tip i.e.

Table I : Thermal Data of Steel[3]

Item	Symbol	Unit	Value
Density	ρ	Kg/m^3	7200
Heat capacity	Cp	J/Kg°K	500
Conductivity	K	J/m/s/°K	50
Resistivity	ρ_e	Ohm m	10^{-7}
Ambient Temperature	T_o	°C	25
Melting point	T_{mp}	°C	1500

$M_R = U \rho \pi d^2 /4$ ....(2)

ρ is density of metal and U feed rate. From equations (1) and (2), it follows that smaller size electrodes will have higher melting rate at certain current than the bigger size electrodes. In order to match higher melting rate and lower cross section of the wire, smaller size must be fed at much higher speeds through the guide and the contact tube than the bigger size electrode. Computed melting rate and feed rate of the electrode made of steel are plotted against current for different size electrodes in Figs. 1 and 2 respectively. Thermal data of steel used in computing the values in the present work are summarized in Table I.

Heat Flow in the Electrode

The tip of the electrode must reach the melting point of the material before it could be melted off. Heat balance gives the following differential equation to describe the temperature distribution in the electrode :

$$\rho C_P (\pi d^2 /4) (dT_z /dt) = K (d^2Tz /dZ^2) \pi d^2/4 + \rho C_P U (\pi d^2/4) (dTz/dZ) - h (Tz-To) \pi d + 4 I^2 \rho_c /\pi d^2 \quad ....(3)$$

C_P is the heat capacity of the electrode material, K thermal conductivity in J/m/s/°K, Tz temperature at distance Z from the tip of the electrode, T_O ambient temperature and h is the heat transfer coefficient. Other symbols

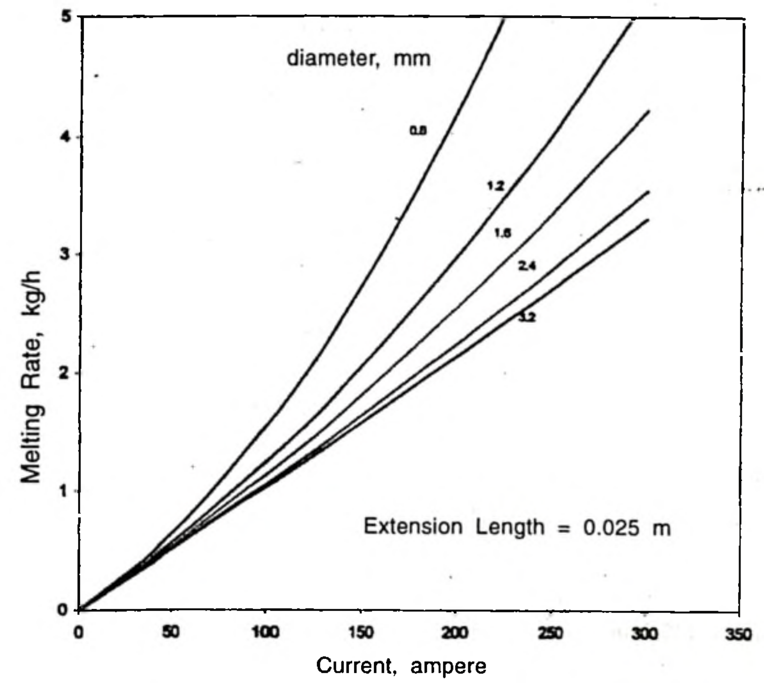

Fig. 1 : Melting Rate versus Current Plots for Arc Welding Processes using Consumable Electrode.

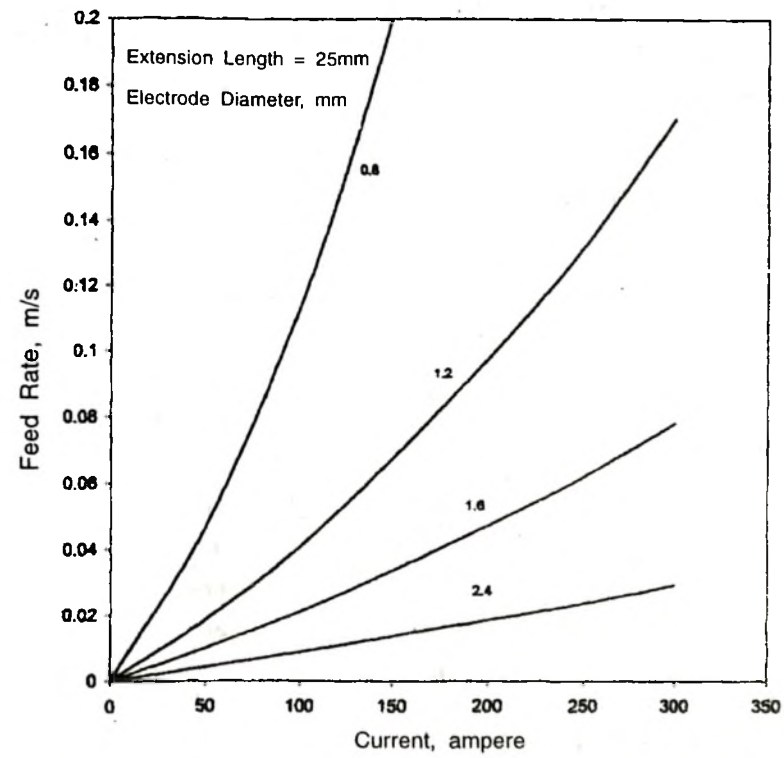

Fig. 2 : Feed Rate versus Current Plots for gas Metal Arc Welding

used in equation (3) have been explained before. Heat flow is assumed to occur along the electrode axis only. The radial heat flux is ignored because of the small cross section area of the electrode compared to the length. Numerical method such as finite difference may be used to solve the differential equation with a set of one initial and two boundary conditions. The electrode length is divided into a large number of grids. Each grid is given a step change in temperature after small time interval. Computation diffusivity must exceed the thermal diffusivity of the material for the method to succeed i.e. :

$$\delta^2/s >> (K/\rho C_p) \qquad ....(4)$$

δ is the length of the element under consideration and s the time interval for the step change in temperature of the element.

(dTz/dt), (d^2T_Z/dZ^2) and (dT_Z/dZ) in equation (1) are discretized as follows :

$$(dT_Z/dt) = \{Tz^{t+s} - Tz^t\}/s \qquad ....(5)$$

$$(d^2T_Z/dZ^2) = \{Tz+_\delta + T_{z-\delta} - 2\ T_z\}/\delta^2 \qquad ....(6)$$

$$(dT_Z/dZ) = \{T_{Z+\delta} - T_Z\}/\delta \qquad ....(7)$$

Initial and boundary conditions may be expressed as follows :

$$T = T_{mp} \quad \text{at } Z=0 \quad t > 0 \qquad ....(8)$$

$$T = T_O \quad \text{at } Z>0 \quad t = 0 \qquad ....(9)$$

One more boundary condition is to be described in order to solve the equation. This will depend upon the process as mentioned below.

Gas Metal Arc Welding

The metal picks up current and temperature due to its resistance heating as and when the electrode wire passes through the electrical contact tube. Extension length of the electrode wire remains more or less constant with time. The boundary condition to solve the equation (3) may be written as follows :

$$T_L = T_O \quad \text{at } Z=L \text{ and } t>0 \qquad ....(10)$$

Computed temperature by solving the differential heat flow equation (3) by the numerical method is plotted against distance along the electrode axis from the tip in Fig. 3. Results of computation show that the temperature distribution as a function of distance from the tip of the electrode does not change with time after a short duration of less than one second or so. Assuming quasi steady state and ignoring surface heat losses, equation (3) reduces to :

$$K\ (d^2T_Z / dZ^2)\ \pi d^2/4 + \rho C_P U\ (\pi d^2/4)\ (dT_Z / dZ) + 4I^2 \rho_e / (\pi d^2) = 0 \qquad ...(11)$$

$$T = T_{mp} - [T_{mp} - T_O - 16\ I^2\ KL\ \rho_e / (\pi^2 d^4\ U\rho C_P)] / \{1 - \exp\ (-\rho C_P UL / K)\} - 16 I^2\ KZ\ \rho_e / (\pi^2 d^4\ U\rho C_P) + [\ T_{mp} - T_o - 16 I^2\ KL\rho_e / (\pi^2 d^4\ U\rho C_P)]\ (\exp\ (-\rho C_p UZ/K) / \{1 - \exp (-\rho C_p UL/K) \qquad ....(12)$$

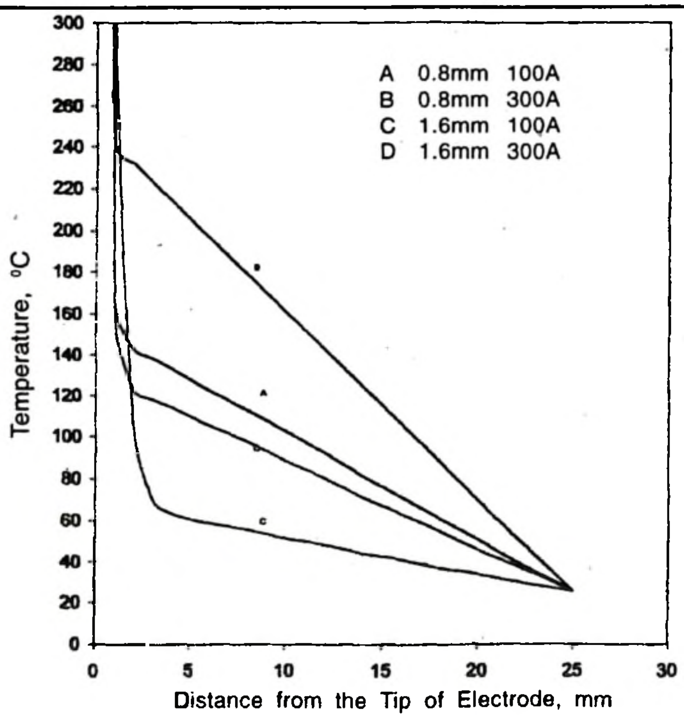

Fig. 3 : Computed Temperature versus Distance Plots in Gas Metal Arc Welding

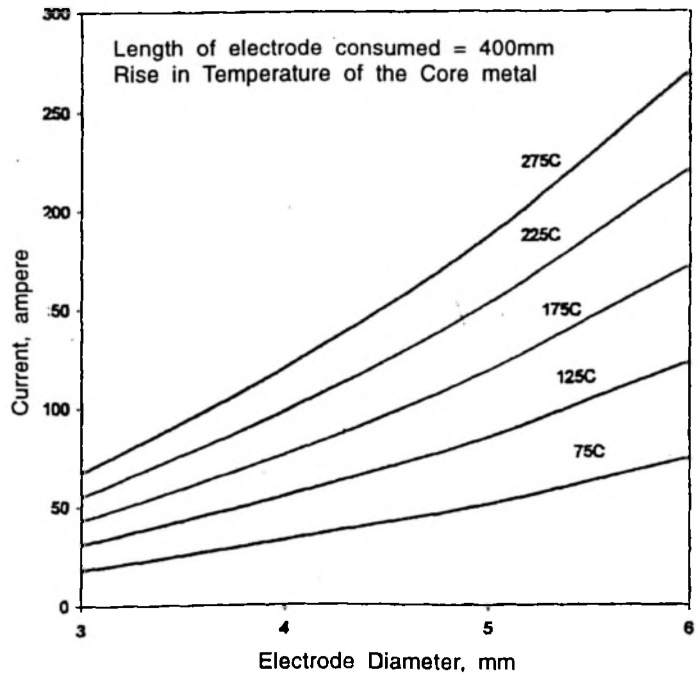

Fig. 4 : Limiting Current versus Diameter Plots in Shielded Metal Arc Welding

The solution to equation (11) with stated boundary conditions in equations (8) and (10) is given below :

First term due to conduction in the equation (11) is significant in the vicinity of the tip of the electrode and it would contribute little to the rise in temperature of the material beyond 2 mm or so from the tip. Ignoring heat conduction in the wire, temperature distribution within the electrode wire away from the tip would be given as follows :

$$(dT_Z/dZ) = -16I^2\rho_c/\pi^2 d^4 \rho C_P U) \quad ...(13)$$

Solving the equation with the boundary condition given in equation (10), one gets the solution as follows :

$$T_Z = T_O + (16I^2 \rho_c/ (\pi^2 d^4 \rho C_p U) (L-Z) \quad ....(14)$$

Results plotted in Fig. 3 match well with those computed using simplified equation (14) for $Z > 0.003$ m. Heat flow considerations as such may not have much relevance in determining the current rating of the electrodes. However, current rating might be governed by the rate at which the wire could be fed without having frequent disruptions in the process due to formation of kick etc. For example, if the feed rate is limited to around 5m/min, current rating of 0.8 mm diameter wire comes to be less than 80A and that of 1.6 mm diameter wire around 300 A.

Shielded Metal Arc Welding

Electrodes in shielded metal arc welding are supplied in certain sizes of finite length. To solve equation (3) using numerical methods, one may apply the following boundary condition :

$$dT_Z/dz = 0 \text{ at } Z=L_e \text{ and } t>0 \quad ...(15)$$

Le is the length of the electrode at any instant. Presence of flux layer in the covered electrode acts as an insulation layer and it reduces the heat losses. The length of the electrode decreases with time as the mass is melted off at the tip. For practical reasons, the electrode pieces of less than 50 mm are discarded. Further welding, if required, is carried out using a fresh electrode. Conduction terms are not significant in determining the temperature reached by the region 10 mm or more away from the tip of the electrode. Metal gets resistance heated at a uniform rate throughout the length due to the flow of current. Temperature gradient in the axial direction may be ignored. Ignoring first three terms on the right hand side of the equation (3), one may get the simplified expression of heat flow as follows :

$$dT_Z/dt = 16I^2 \rho_c/ (\pi^2 d^4 \rho C_P) \quad ...(16)$$

Initial condition to solve the above equation is given in equation (9). Solving,

$$T_Z = T_O + (16I^2 \rho_c/\pi^2 d^4 \rho C_P) t \quad ...(17)$$

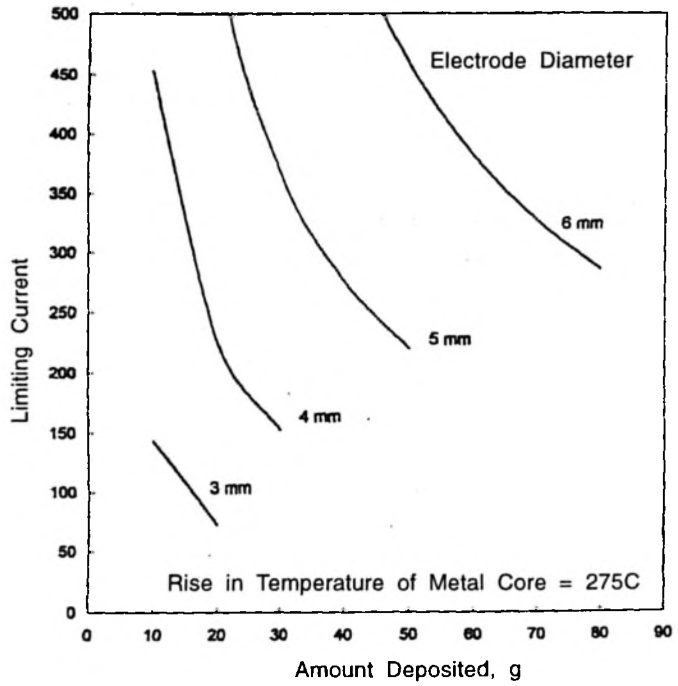

Fig. 5 : Limiting Current versus Weight Deposited Plots for Shielded Metal Arc Welding

Contribution of the resistance heating of the wire to its melting rate i.e. second term on right hand side of equation (1) may be ignored for the covered electrodes in shielded metal arc welding process as stated before. Combining equations (1) and (2), the average feed rate of electrode may be expressed in terms of current and diameter as follows :

$$U = 4\alpha I/(\rho\pi d^2) \qquad ...(18)$$

Length of electrode that would be consumed in certain time is the product of average feed rate and time i.e.

$$\Delta L = L_o - L_e = 4\alpha \; I\,t/(\rho \;\pi d^2) \qquad ...(19)$$

Time taken to melt certain length of the electrode is, thus, related to current and electrode diameter as follows :

$$t = \rho\pi d^2 (L_O - L_E) \;/\; 4\alpha \; I \qquad ....(20)$$

Equation (20) shows that time to melt a certain length of the electrode at a stretch would decrease with an increase in current. However, temperature reached by the material in melting off certain length of the electrode could increase with an increase in current as shown below mathematically by combining equations (17) and (20) :

$$T_Z = T_O + (4I\,\rho_e(L_O - L_e) / (\pi d^2 \alpha C_P) \qquad ....(21)$$

Equation (21) may be used to determine the current rating of the electrode if the safe temperature to which the electrode covering may be heated without undergoing premature decomposition is known. Current versus diameter plots for different temperatures are shown in Fig. 4. The amount of metal deposited is related to length of the electrode consumed and the diameter as follows :

$$W = \rho\pi d^2 \;(L_O - L_E)/4 \qquad ....(22)$$

Actual current rating of an electrode could depend upon the actual amount of metal to be deposited to complete welding of a joint. In general, current rating of an electrode will be increased for depositing lesser amount of metal and vise versa Mathematically one may get the following : i.e.

$$I = \rho\, C_P\, \alpha (T_{max} - T_O)\{\pi d^2/4\}^2 / (\rho_e W) \qquad ....(23)$$

W is the amount of metal to be deposited and Tmax is the temperature that the electrode could reach for safe working. Current versus weight plots for different sizes of electrodes are shown in Fig. 5.

SUMMARY AND CONCLUSION

1. Mathematical equations and computer programs are developed to solve one dimensional heat flow in electrodes of arc welding processes.

2. For arc welding processes where the electrode wire is fed continuously through the electrical contact tube, extension length of the electrode remains constant. Current rating of the wire might be limited by the feed rate of the wire that could be maintained for the trouble free operation.

3. For shielded metal arc welding, current rating of the covered electrodes is limited mainly by the temperature which the core metal may reach due to resistance heating of the material.

REFERENCES

1. R. L. O'Brien (ed) 'Welding Handbook Volume 2' AWS Miami (1991).
2. R. S. Parmer 'Welding Processes and Technology' Khanna Publishers, New Delhi (1993).
3. Taylor Lyman (ed) Metals Handbook Vol. 1' ASM Metals Park, Ohio (1961).

■