Calculation of the depth of penetration in Electron Beam Welding

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Recent advances in space and nuclear technology need the use of such metals as zirconium, titanium, tantalum etc. which are not easily weldable by the conventional welding methods. In recent times, EBW has been successfully employed to fabricate parts made out of these materials. But the application of EBW need not be restricted to the welding of these metals only. Since welding by electron beam is characterised by the fact that it is possible to obtain large depths of penetration with narrow heat affected zones with minimum of distortion and defects, this method of welding is now being widely used for the fabrication of heavy sections of low alloy steels, stainless steels, aluminium etc. In addition, the welding parameters can be very finely controlled. To take advantage of these factors it becomes necessary to calculate the optimum parameters of welding for a given depth of penetration.

The following are some of the parameters which affect the depth of penetration in electron beam welding:

1. Electron beam current (I) : This is characterised by the number of electrons which travel from cathode to anode i.e. to the job. The power in the beam, which is one of the parameters of the process, is obtained as a product of the beam current and the accelerating voltage. Investigations show that the depth of penetration increases with the increase in current /1,2/.

2. Accelerating voltage (U) : The kinetic energy of the electrons is a function of the accelerating voltage. The dependence of the depth of penetration on accelerating voltage may be linear or nonlinear /2/. This can be explained by the peculiarities of the particular electron gun used and the electron optic system.

3. Diameter of the beam (d_1) : The energy density of the electron beam is strongly dependent on the diameter of the beam at the point of contact of the beam with the job. The smaller the diameter of the beam the greater will be the energy density and consequently the greater will be the depth of penetration /2/.

4. Welding speed (V) : An increase in the welding speed brings about a decrease in the energy per unit length of the weld and hence a decrease in the depth of penetration /1, 2/.

The above parameters can be easily controlled. But in addition the thermophysical properties of the material too affect the depth of penetration. These parameters must be taken into account while deriving an equation for the depth of penetration.

The heat energy that is lost by conduction from the zone of welding to a large extent depends upon the coefficient of thermal conductivity λ. At first glance it appears that with an increase in the thermal conductivity the heat lost from the weld zone increases bringing about a decrease in the depth of penetration. However it has been shown /3/ that if for some metals the depth of penetration decreases with an increase in the coefficient of thermal conductivity, a number of metals do not follow this rule.

The specific heat of the metal being welded (c), its latent heat (r) and the melting point (T_m) determine the amount of heat necessary to melt a given volume of the metal.

Taking the above mentioned parameters into account by dimensional analysis, it is possible to obtain an equation to determine the depth of penetration in electron beam welding.

The general equation for the determination of the depth of the penetration can be written as :

$$h = K_1 q^a \lambda^b C^e r^d d_1^g V^m T_m^n \qquad (1)$$

where h—depth of penetration

K_1, a, b, e, d, g, m, n—constants

$q = \eta . U . I$

η—is the efficiency.

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Equation (1) can be reduced to the following form after inserting the relevant dimensions of the physical quantities involved :

$$L=K_1(Ht^{-1})^a(HL^{-1}\theta^{-1}t^{-1})^b(HL^{-3}\theta^{-1})^e(HL^{-3})^d L^g(Lt^{-1})^m\theta^n \qquad (2)$$

where H, L, θ and t are dimensions of quantity of heat, length, temperature and time respectively.

Solving equation (2) it is possible to show that :

$$\frac{h}{d_1}=K_1\left(\frac{q}{d_1\lambda Tm}\right)^a\left(\frac{CVD_1}{\lambda}\right)^m\left(\frac{r}{CTm}\right)^d \qquad (3)$$

However, equation (3) contains four constants K_1, a, m and d. These are very difficult to determine. The same problem can be solved more conveniently if it is possible to increase the number of independent dimensions of measurements.

Huntley /4/ showed, if needed, the number of fundamental dimensional quantities of length, mass and time may be increased by resolving the dimensions of the length along three mutually perpendicular planes. These "fundamental dimensions" may be called as the vector dimensions of length by the indexes/L_x/,/L_y/,/L_z/.

According to this convention the speed of welding has the dimensions of L_xt^{-1}, volume has the dimension $L_x.L_y.L_z$. If the heat lost is parallel to the OY axis.

$$[\lambda]=L_y.L_x^{-1}.L_z^{-1}.H.\theta^{-1}.t^{-1}$$

Let the Z axis be oriented in the direction of the electron beam. Then $[h]=L_z$.

The diameter of the beam at the point of contact with the metal is axisymmetric relative to OZ. Therefore the diameter has the dimensions $[d_1]=L_x^{\frac{1}{2}}.L_y^{\frac{1}{2}}$.

Taking in to account the vector characterisitics of the dimensions of the length we get the following table :

Table 1

Physical quantity	*Symbol*	*Dimensional equation*
Depth of penetration	h	L_z
Heat input per unit time.	q	$H\ t^{-1}$
Coefficient of ther. conduct.	λ	$L_x^{-1}L_yL_z^{-1}H\ \theta^{-1}\ t^{-1}$
Volume specific heat.	c	$L_x^{-1}L_y^{-1}L_z^{-1}H\ \theta^{-1}$
Latent heat of fusion.	r	$L_x^{-1}L_y^{-1}L_z^{-1}\ H$
Diameter of the beam.	d_1	$L_x^{\frac{1}{2}}\ L_y^{\frac{1}{2}}$
Speed of welding.	V	$L_x\ t^{-1}$
Melting temperature.	T_m	θ

Hence the equation (2) takes the following form :

$$L_z=K_1(Ht^{-1})^a(H\theta^{-1}L_x^{-1}L_yL_z^{-1}t^{-1})^b(H\theta^{-1}L_x^{-1}L_y^{-1}L_z^{-1})^e (HL_x^{-1}L_y^{-1}L_z^{-1})^d(L_x^{\frac{1}{2}}\ L_y^{\frac{1}{2}})^g(L_xt^{-1})^m.\theta^n \qquad (4)$$

By equating the indices a, b, e, d, g, m and n on the right hand side to the indices on the left hand side of the equation (4) we get

For L_x $\quad 0=-b-e-d+\frac{1}{2}g+m$

For L_y $\quad 0=b-e-d+\frac{1}{2}g$

For L_z $\quad 1=-b-e-d$

For θ $\quad 0=-b-e+n$

For H $\quad 0=a+b+e+d$

For t $\quad 0=-a-b-m$

By solving these simultaneous equations we get $a=1$, $b=-1/3$, $e=e$, $d=-2/3-e$, $g=-2/3$, $m=-2/3$, $n=-1/3+e$

Substituting these values in equation (4) we get

$$h = K_1\frac{q}{(\lambda r^2d_1^2V^2Tm)^{\frac{1}{3}}}\left(\frac{CTm}{r}\right)^e \qquad (5)$$

In equation (5) it is necessary to find only two constants K_1 and e.

Since for a given material the non dimensional parameter $\left(\frac{C\ Tm}{r}\right)$ is a constant, we can write equation (5) as

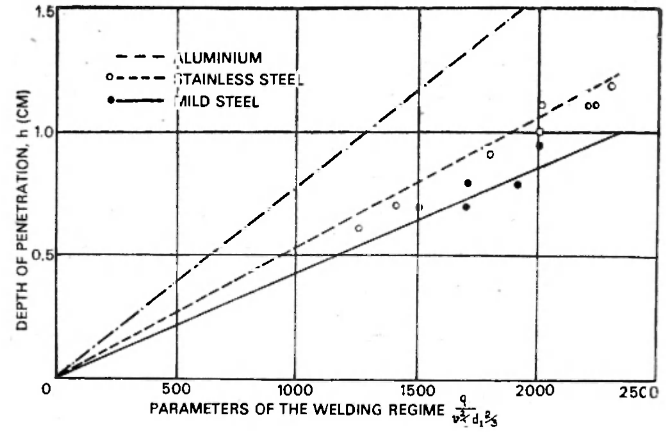
$$h=K_2\frac{q}{(\lambda r^2d_1^2V^2Tm)^{\frac{1}{3}}} \quad \text{where } k_2=K_1\left(\frac{CTm}{r}\right)^e$$

The thermophysical properties of some of the metals used in the calculations are shown in table 2.

Table 2

Metal	C cal	λ cal	Tm	r cal
	$cm^3.°C$	cm.sec.°C	°C	cm^3
Low carbon steel	1.14	0.09	1500	510
Stainless steel	0.95	0.06	1460	510
Aluminium	0.60	0.53	660	255

Fig. 1 shows the depth of penetration as a function of the parameter $\frac{q}{(Vd_1)^{\frac{2}{3}}}$ where q is the electron beam power. These graphs are obtained after analysing



the data of Hashimoto and Matsuda /5/. From these graphs the value of the constant K_2 was determined by a least square fit /6/.

The following equations for finding the welding parameters for a given depth of penetration are recommended :

For mild steel : $$h=13.10^{-2}\frac{q}{(\lambda r^2 d_1^2 V^2 \, Tm)^{\frac{1}{3}}}$$

For stainless steel : $$h=15,10^{-2}\frac{q}{(\lambda r^2 d_1^2 V^2 \, Tm)^{\frac{2}{3}}}$$

For aluminium : $$h=22.10^{-2}\frac{q}{(\lambda r^2 d_1^2 V^2 \, Tm)^{\frac{1}{3}}}$$

In fig. 1 the experimental results obtained by us during electron beam welding of stainless steel and mild steel are shown. It can be seen that the experimental and theoretical results agree fairly well.

Conclusions

1. By dimensional analysis an equation for the depth of penetration in electron beam welding has been obtained.

2. The following equations for the calculation of the depth of penetration are recommended :

For mild steel : $$h=13.10^{-2}\frac{q}{(\lambda r^2 d_1^2 V^2 \, Tm)^{\frac{1}{3}}}$$

For stainless steel : $$h=15.10^{-2}\frac{q}{(\lambda r^2 d_1^2 V^2 \, Tm)^{\frac{1}{3}}}$$

For aluminium : $$h=22.10^{-2}\frac{q}{(\lambda r^2 d_1^2 V^2 \, Tm)^{\frac{1}{3}}}$$

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