PREDICTION OF WELD PENETRATION IN ELECTRON BEAM WELDING OF CARBON STEEL THICK SECTIONS

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الملخص

إن إنجاز عمليات اللحام بمعدلات حرارة دخل منخفضة يقلل من مدى التغيرات الميتالورجيه والإجهادات المتبقية لمعدن الأساس. لحام القطاعات السميكة يتطلب حرارة دخل عالية والتي تؤثر على خواص وصلات اللحام. يتميز اللحام بالحزمة الإلكترونية على قدرته العاليـــة على التغلغل وعدم اتساع درزة اللحام (Weld bead) مع انخفاض معدل حرارة الدخل (Heat input) المستخدمة مقارنة بطرق اللحام الأخرى. من المعروف أن عمق التغلغل في وصلات اللحام يزداد كلما انخفضت سرعة اللحام (ازدياد حرارة الدخل). هذه الورقة تعرض نتائج علاقة سرعة اللحام بعمق التغلغل في لحام الحزمة الإلكترونية لوصلات من الصلب الكربوني ومقارنة النتائج مع عمق التغلغل المتوقع نظرياً. أوضحت النتائج أن تقدير عمق التغلغل نظرياً في وصلات اللحام السميكة لا يتطابق مع عمق التغلغل الفعلي والذي يقل عن العمق المتوقع أما في وصلات اللحام الأقل سمكاً فإنه يمكن حساب عمق التغلغل نظرياً والذي وافق النتائج المعملية في لحام الحزمة الإلكترونية.

ABSTRACT

This paper presents the results of a work carried out on Electron Beam Welding (EBW) of carbon steel thick sections. It was aimed to study the effect of varying the welding speed of EBW on weld penetration. It is well known that reducing the welding speed will increase the weld depth. However, it is worth investigating the manner the penetration depth varies with welding speed and the possibility of using the Rosenthal equation to predict the weld penetration in EBW.

Welding thick sections using butt joints encountered technical problems in this study including the precise fit and tolerance of weld joints for EBW. Using seam weld T-joint is more practical regarding the research aim of this work. T-joints used in this work were consisting of two plates with the same thickness. Three joints with plate thicknesses of 10 mm, 15 mm and 20 mm were welded by EBW using welding speeds of 400, 175 and 100 mm/min respectively with welding current of 160 mA and voltage of 65 kV. Penetration depths obtained at these welding parameters were compared with theoretical predictions based on Rosenthal equations. The criterion to define the plate thickness depends on the manner of heat dissipation from the fusion zone to the base metal. Heat input as well as plat thickness determines the critical thickness above which a joint is dealt with as a thick plate. The adopted solution is either the two dimension solution applied for joints considered as thin or the three dimension solution when the plate thickness of the joint is considered thick. In this work the two dimension solution is applied for the first joint and the three dimension solution for the other two joints.

Results showed agreement between theoretical predictions and real observations for the first joint with welding speed of 400 mm/min. For the other two joints with lower welding speeds penetration was overestimated by the theoretical prediction. Discrepancy between observed penetration and predicted values increased with decreasing welding speed (increasing heat input). Better prediction of weld penetration was obtained with a modified three dimension solution of Rosenthal equation.

Weld depth using EBW can be predicted with Rosenthal equations when welded sections are considered as thin joint. For thick sections the three dimension solution can be adopted with small modification on Rosenthal equation.

KEYWORDS: Electron Beam Welding (EBW); Rosenthal equation; Welding speed; Heat input.

INTRODUCTION

Metal joining by Electron Beam Welding finds new applications in all aspects of industry. This is because EBW provides a different approach to solve some technical problems in metal joining not available by other techniques. The exploit of electron beam and its characterization made it possible to achieve great successes in many welding applications. Despite the high capital cost of the method, advantages offered by EBW counterbalance this limitation. Among the unique merits of EBW is its deep penetration accompanied with narrow width of the weld metal [1, 2, 3]. Other valuable features include the ability to perform weld when accessibility is a real difficulty and perform surface treatment [4]. Recent development in electronic devices allowed the use of multi-beam processes [5]. This provides the method with great potential especially in manufacturing of sophisticated devices over other techniques and justifying the widespread of the technique as an important industrial tool in recent years. Therefore this method is progressively improving to reach higher limits. This is achieved through a better understanding of all parameters that affect the welding operation along side with developments in EBW welding equipments. Welding of thick sections is one area where EBW showed superiority on many other methods. Most conventional methods encounter some sort of difficulty regarding welding thick sections. Multipass techniques usually the solution for this task in most welding methods other than submerged arc welding. The time consuming, the high skill required and the immense heat delivered in the process reduces the favorability of adopting conventional methods in such applications. To achieve deeper penetrations in thick sections, welding parameters such as current, potential and welding speed should be carefully selected. In EBW in addition to the mentioned parameters, other parameters such as beam focus and spot diameter also influence the welding process. Selecting optimum parameters therefore is very crucial in obtaining successful welding. In this work the effect of welding speed in welding of carbon steel thick sections was studied. Mathematical analysis was carried out to put prediction of weld penetration at various heat inputs. Theoretical estimations and real observations of welding penetrations were compared in this work.

MATERIAL AND METODOLOGY

Joints Preparation

Three T-joints were prepared with three different thicknesses. The chemical composition on the welded steel is shown in Table (1). Each joint consist of a flat plate and a vertical plate of the same thickness. The plate thicknesses were 10 mm, 15 mm and 20 mm. These three joints will be assigned the letters A, B and C for joints of plates with 10, 15 and 20 mm respectively. Matching surfaces of joints for EBW were ground to obtain intimate contact.

Table 1: Chemical composition of the steel in wt%

C	Mn	P	S	Si	Fe
0.2	0.72	0.05	0.05	0.1	balance

Plates then cleaned thoroughly and tack welded using TIG welding to prepare the Tee joint. The welding technique was performed horizontally on the flat plate on the other side of the vertical plate as shown schematically in Figure (1). Vertical plates were cut slightly longer than flat plates. This prevents masking the ends of the vertical plate by the flat plate when joints are placed in the vacuum chamber. This allowed the welder to determine the start and end points to ensure the welding line do not deviate from the predetermined path. The outstanding penetration ability of EBW allows this joint to be welded by the above explained technique so that the bottom of the vertical plate is melted and welded to the flat plate as shown schematically in Figure (2).

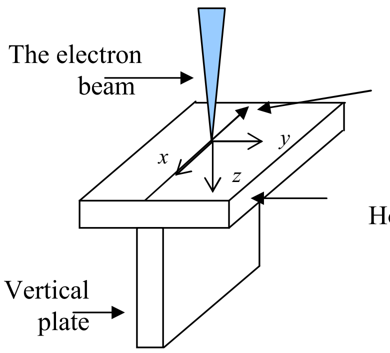


Figure 1: Shows the joint design, the electron beam, the weld line and the coordinate system

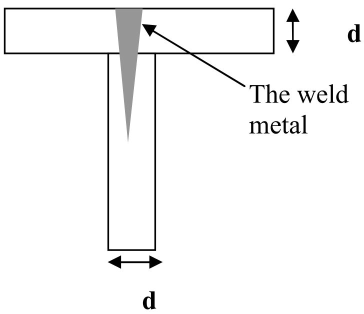


Figure 2: Schematic drawing of the welded T joint by EBW

Welding Technique

EBW carried out at high vacuum of 8.5×10^{-5} mbar using electron beam welding machine Techmeta type Lara 250. The welding parameters for each joint were fed into the welding machine. Joints were placed with vertical plate beneath the flat plate so that the flat plate is exposed to the electron beam. Two joints for each thickness were welded. Higher penetration depth is required when welding thicker joints. This was achieved through increasing the weld heat input by decreasing the welding speed as the joint thickness increases. All other parameters were kept unchanged except the working distance which shortened as the plate thickness increases. Welding parameters for EBW are presented in Table 2.

Table 2: Welding Parameters

Variable	Joint A (10 mm thick)	Joint B (15 mm thick)	Joint C (20 mm thick)
Voltage (kV)	65	65	65
Current (mA)	160	160	160
Welding speed (mm/min)	400	175	100
Vacuum (mbar)	8.5×10^{-5}	8.5×10^{-5}	8.5×10^{-5}
Focus type	Sharp surface	Sharp surface	Sharp surface
Work distance (mm)	500	495	490
Focus current (A)	1.86	1.86	1.86

Weld penetration measurements

Joints examined under optical microscope at various magnifications. The microscope stage is provided with two micrometers placed at right angles. This allowed measuring penetration depth and width of the weld joint while examining the joint under the optical microscope.

Weld penetration prediction

A solution proposed by Rosenthal relates the welding heat input to the size of the weld pool [6,7]. The solution distinguishes between thin and thick joints. Joints are considered thin when variation in thickness affects the cooling rate of the weld joint. When cooling rate becomes independent of joint thickness, the joint is considered thick. The cooling time Δt_{8-5} versus plate thickness is related to the heat input (or welding speed) as follow [8].

$$\Delta t = \frac{(q/v)^2}{4\pi\lambda\rho c\theta^2 d^2} \tag{1}$$

where q is the heat input in (J/sec), v is the welding speed in (m/sec), λ is the thermal conductivity in $(J/m\ sec\ K)$, ρc is the volume thermal capacity in $(J/m^3\ K)$, *d* is the plate thickness in (m) and θ^2 is

$$\frac{1}{\theta^2} = \frac{1}{(773-T_o)^2} - \frac{1}{(1073-T_o)^2} \tag{2}$$

where T_o is the initial temperature = 298 K

According to equation (1) the cooling time versus the plate thickness for the three applied welding heat input rates (welding speed) is as shown in Figure (3).

The critical thicknesses (d_c) can be estimated from Figure (3) or according to equation (3) [6].

$$d_c = \left[\frac{q}{2\rho c v} \times \left(\frac{1}{773 - T_o} + \frac{1}{1073 - T_o} \right) \right]^{1/2} \tag{3}$$

where d_c is the critical thickness in mm and T_o is the initial temperature (or preheat temperature) in K. The critical thicknesses for the three joints are as follow: for joint A with welding speed of 400 mm/min the critical thickness is 10 mm, for joint B with welding speed of 175 mm/min the critical thickness is 23 mm and for joint C with welding speed of 100 mm/min the critical thickness is 38 mm respectively. Comparison of critical thickness and real joint thicknesses is presented in Figure (4).

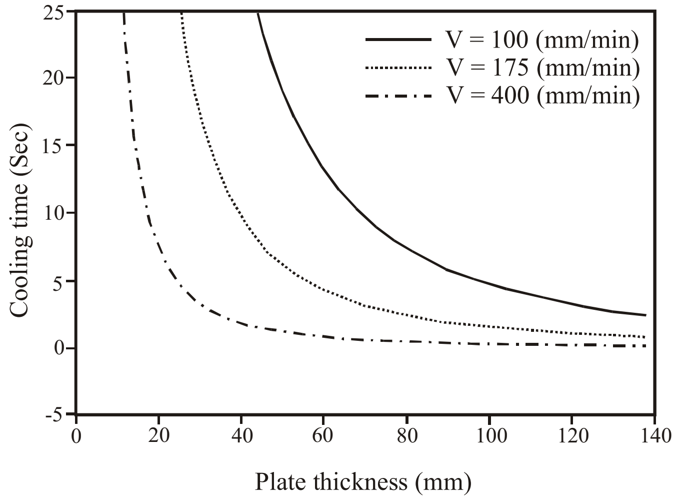


Figure 3: Shows the effect of welding speed and plate thickness on cooling time

The two dimension Rosenthal solution applied for thin plate is [8].

$$T - T_o = \frac{q/v}{2\pi\lambda t} \exp\left(\frac{vx}{2\alpha}\right) K_o\left(\frac{vr}{2\alpha}\right) \tag{4}$$

where α is thermal diffusivity in (m^2/sec), K_o is modified Bessel function of the second kind and zero order, t is the plate thickness in m, r is the radial distance from origin equals ($\sqrt{x^2 + y^2 + z^2}$) where x, y and z are distances from the origin coordinate in three perpendicular directions, x is in the negative welding direction, y in the lateral direction on the surface and z beneath the origin.

The three dimension Rosenthal solution for thick plate is

$$T - T_o = \frac{q/v}{2\pi\lambda r}\exp\left(\frac{-v(r-x)}{2\alpha}\right) \tag{5}$$

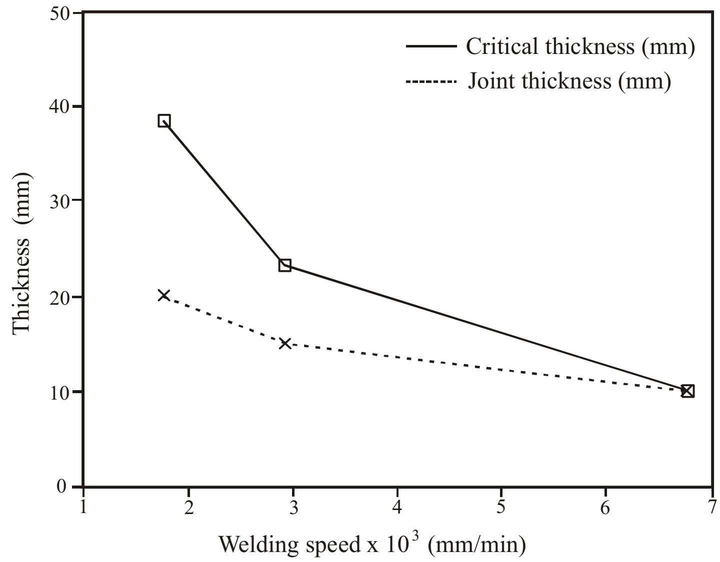


Figure 4: Comparison of critical thickness with real joint thickness

RESULTS

Weld penetration

Predicted weld penetrations are obtained from Figure (5). This figure shows the variation of temperature along the joint thickness at the weld centre line and just behind the heat source i.e. y = 0 and x = 0 for joints A, B and C.

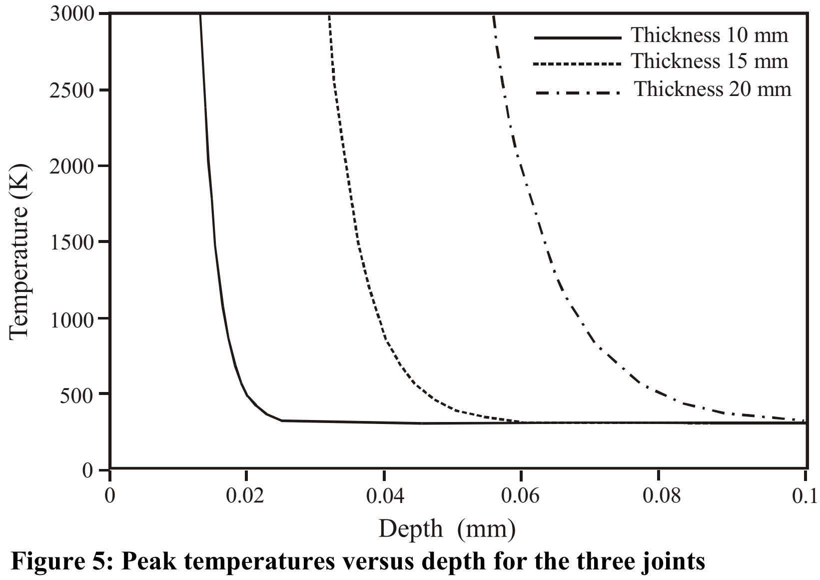
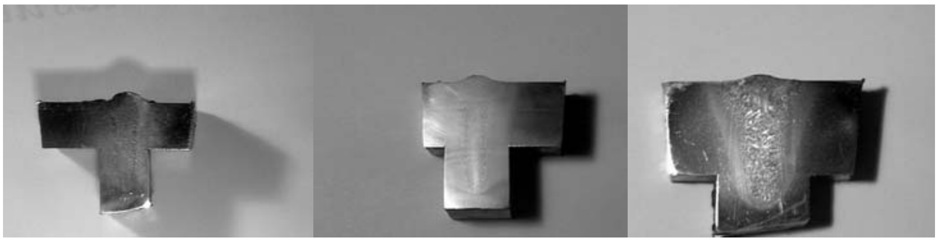


Figure 5: Peak temperatures versus depth for the three joints

This figure is obtained using thin plate solution for joint A and thick pate solution for joints B and C. The weld penetration is taken as the depth corresponding to the temperature of 1800 K which is approximately the melting point for the steel. Figure (6) shows cross sections macrostructure for the three welded joints. The results of observed and predicted (estimated) penetrations are summarized in Table (3) and Figure (7).



Joint A Joint B Joint C

Figure 6: Macrostructure of cross sections for the three joints

Table: 3 Observed and predicted weld penetration

Joint	Observed penetration (mm)	Predicted penetration (mm)
A	17	15
B	25	34
C	27	61

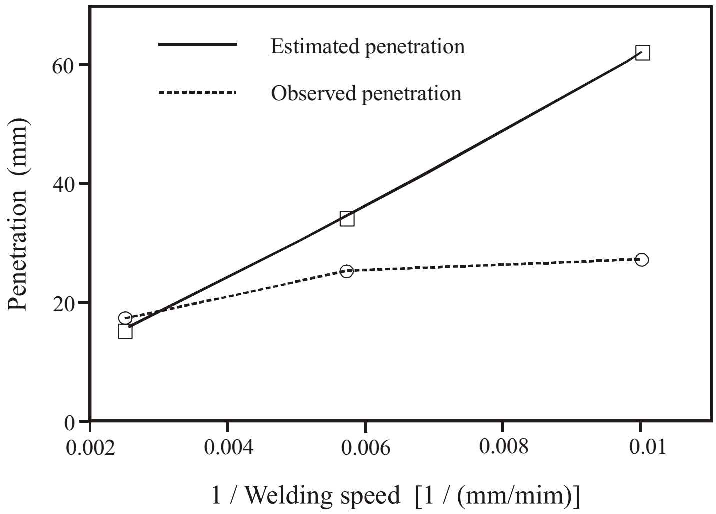


Figure 7: Comparison of observed and predicted weld depth for various welding speeds.

DISCUSSION

Figure (7) shows a linear relation between predicted penetration depths and reciprocal of welding speed. The observed penetration values increased with much less rate compared with predicted values and shows tendency to level off as the welding speed decreases. The only agreement between estimated and observed penetration is found for joint A. As the joints thickness increases the discrepancy between the two lines in Figure (7) increase. The manner the estimated values vary with welding speed would predict extremely high penetration if extrapolation made to very slow welding speeds. It will be less rational to accept such a trend for penetration depths variation with welding speed.

The linear relation would be expected when thickness of joints are in order of few millimeters. As the joint thickness increases, greater proportion of the base metal is melted and more heat is dissipated to the base metal. This means larger proportion of energy input is consumed before reaching higher depth in the workpiece.

A larger volume of material therefore is melted in thicker joints in order for penetration to reach higher depths. This may be explained by calculating the volume of the weld metal in each weld joint. Figure (8) shows a schematic drawing represents the molten metal in EBW joint where w is the width and d is the weld penetration. The area of the triangle is $d^2 \tan\left(\theta/2\right)$. On the basis of 1 minute time the travel distance of the electron beam is 400 mm, 175 mm and 100 mm for joints A, B and C respectively. The molten metal volume is then the product of the triangle area by the travel distance. The calculated volumes of molten metal and their relative volumes are indicated in Table (4).

Area = $d^2 \tan\left(\theta/2\right)$

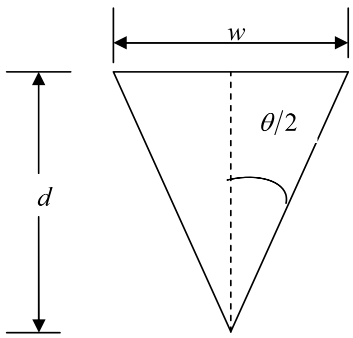


Figure 8: schematic drawing representing the molten metal in a welded joint.

Calculations of volumes of molten metals shows that reducing the weld speed causes larger volume of metal fused in the same time interval. In order for the beam to penetrate deeper, more metal is melted side ways of the beam and more heat dissipated also to the base metal. This renders deeper penetration more difficult. Therefore, the linear relationship predicted by Rosenthal equations as indicated in Figure (7) will not be applicable for very thick joints as is the case in the current work. The observed results of penetration therefore are consistent with this analysis.

Table 4: Characteristics of molten metal in the three welded joints

Joint	d (mm)	w (mm)	area (mm^2)	travel $distance\ (mm)$	volume (mm^3)	$\frac{d}{w}$	relative volume
A	17	5	.074	400	296.4	3.4	100 %
B	25	10	2.18	175	381.5	2.5	129 %
C	27	17	4.01	100	401.0	1.6	135 %

The increased volume of fused metal is evident from the decreasing of depth to width ratio (d/w) as indicated in Table (4). If the depth to width ratio is considered as the criterion for the efficiency, then the efficiency decreases at slower welding velocities. In order to increase the penetration depth more efficiently the accelerating voltage should be increased rather than decreasing the welding speed at the same level of heat input rate. However parameter optimization for high (d/w) necessitate study of other important parameters in EBW which influence the weld shape [9].

A curve fitting correlate the penetration depth (P) to welding speed (v) according to the following equation:

$$P=100(1/v)^{3.5}$$

showed good agreement with observed depth penetration.

Accordingly when the Rosenthal equation is modified so that the welding speed term is raised to the reciprocal of 3.5 showed better agreement with real observation. However a similar modification to the two dimensional equation resulted in underestimation of penetration. Therefore the two dimensional solution is applied without any modification while the three dimensional solution gives better prediction with the above mentioned modification to Rosenthal equation.

CONCLUSIONS

In this work the effect of welding speed on penetration depth in Electron Beam Welding of thick sections of carbon steels was investigated. Theoretical predictions based on Rosenthal equation were compared with experimental results. The followings are the main points concluded.

- For sections classified as thin plates, the two dimensional solution of Rosenthal equation gives good agreement between predicted and observed penetration in carbon steels using EBW. The predicted weld depth was 15 mm and the observed weld depth was 17 mm.
- For sections classified as thick plates, the three dimensional solution of Rosenthal equation can be applied with modification in order to predict the weld penetration of carbon steel sections in EBW.
- Lowering welding speed increases the weld depth. However discrepancy between observed penetration and theoretical prediction widen as weld depth increases.
- The depth to width ratio decreases with decreasing welding speed.

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