Analytical methods of electron beam power evaluation for electron-beam welding with deep penetration

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Abstract. Existing analytical methods for calculating electron-beam welding modes, which provide welds with required penetration depth, are described, and main disadvantages of these methods are shown. A new calculation method based on a model of moving cylindrical heat source, which involves moving of a cylinder with constant surface temperature in an infinite plate, is proposed. The proposed calculation method takes into account energy losses during metal melting and its partial evaporation. A comparison of experimental and calculated data obtained using the developed method and existing methods, is presented. Plates with a thickness of 32 mm from 5V titanium alloy, 27 mm from 40 Kh13 steel and 20 mm from D16 duralumin were used for experiments. It was shown that the developed method application made it possible to calculate with appropriate accuracy a required beam power during EBW of various materials.

1. Introduction

Beam welding methods for thick-walled structures joining are used in almost all industries [1]. Preliminary calculations of welding modes significantly reduce labor and material costs during welding technology development. Specifically, the main parameter, which is usually used for weld penetration regulation during electron beam welding (EBW), is beam current. There are a large number of methods for establishing the interrelation between beam energy characteristics and weld penetration. Some methods were determined empirically. Such methods usually contain correction factors, due to the complexity of the processes taking place during electron-beam welding. The main disadvantage of empirical methods is that they can be applied correctly only in a quite narrow range of mode parameters and materials being welded. As regards analytical methods, they produce very approximate results; therefore, they are rarely used in practice. Using of numerical methods or complex models of electron beam interaction with a material yields accurate results after verification, but considerable computational power, high cost of software and large process duration severely limit their applicability during production process. At the same time, it is often necessary to determine quickly the required beam current at the stage of EBW technology development or improvement during production process. For example, the transition from EBW on a backing plate to EBW with free formation of weld root, as a rule, requires significant increase in welding speeds, but existing methods cannot achieve acceptable accuracy during recalculation of required beam current. Thus, the problem of appropriate beam current evaluation with the use of minimum time and software resources remains highly relevant. The aim of this paper is the analysis of existing calculation methods and development of the universal analytical method for calculating electron beam power during EBW with deep penetration.
2. Methods of required beam current calculation

During the review several specific calculating analytical methods of establishment interrelation between beam energy parameters and weld dimensions were identified. Several methods are described below. For comfort comparison, in each case, beam current required for penetration of a certain depth was calculated depending on welding speed, and all the remaining parameters were set. Table 1 shows parameters, used for beam current calculation.

Table 1. Parameters for beam current calculation

| Parameter                                      | 5V titanium alloy | 40Kh13 steel | Duralumin D16 |
|------------------------------------------------|-------------------|--------------|---------------|
| Specific heat capacity [J·(kg·K)^-1]           | 530.8             | 452          | 879           |
| Melting temperature [K]                        | 1944              | 1773         | 850           |
| Channel surface temperature [K]                | 2519              | 2508         | 1421          |
| Metal’s density [kg·m^-3]                      | 4505              | 7650         | 2780          |
| Thermal conductivity [W·(m·K)^-1]              | 18.85             | 25           | 119           |
| Specific melting heat [J·kg^-1]                | 470               | 270          | 393           |
| Specific boiling heat [J·kg^-1]                | 9800              | 6300         | 9210          |
| Channel diameter·10^3 [m]                      | 1.1               | 1.1          | 0.7           |
| Weld width mean value·10^3 [m]                 | 2                 | 2            | 2             |
| Nominal penetration depth·10^3 [m]             | 30                | 27           | 20            |

Method 1. The calculation method proposed by I.V. Zuev is based on energy balance in melting zone. For a continuous weld this method is reduced to the equation for beam current calculating:

\[ I = \frac{\pi \cdot B_{mean}^2 \cdot H \cdot S_m \cdot v}{4 \eta_{ef} \cdot \eta_T \cdot U \cdot d}, \]  

(1)

where \( B_{mean} \) is value of weld width; \( H \) is penetration depth; \( S_m \) is heat content of liquid metal at melting temperature; it is determined as \( S_m = \rho(cT_m + L_m) \), where \( \rho \) is metal’s density; \( c \) is metal’s specific heat capacity (J·kg^-1·K^-1); \( T_m \) is melting temperature, K; \( L_m \) is specific melting heat; \( v \) is welding speed; \( \eta_{ef} \) is effective efficiency; \( \eta_T \) is thermal efficiency of welding process, which depends on physical properties of welded material and welding speed; \( U \) is accelerating voltage; \( d \) is diameter of heat source.

The main disadvantage of this method is a necessity to know in advance mean weld width and thermal efficiency of welding processes. Additional experiments to determine these parameters are very time-consuming, thus weld width is set on the basis of experimental data, and thermal efficiency is assumed to be 0.484 as in the case of fast-moving linear heat source. Obviously, a change in welding speed will significantly affect both weld width and thermal efficiency. Therefore, practical use of this method for theoretical determination of welding modes with acceptable accuracy without proper experience is difficult.

Method 2. T. Hashimoto at the start of electron-beam technologies development proposed an equation for calculating penetration depth depending on welding mode parameters and physical properties of the material [2]. This equation is based on a simplified weld formation model. Beam current in this method can be determined by following equation:

\[ I = \frac{H \cdot r_e \cdot v}{U} \left( c \cdot \rho \cdot T_{mean} + \rho \cdot L_m + \frac{5 \cdot \lambda \cdot T_{mean}}{2 \cdot a} + \frac{5 \cdot \lambda \cdot T_{mean}}{2 \cdot \nu \cdot r_e} \right), \]  

(2)

where \( r_e \) is beam effective radius, which is taken as \( d/2 \), \( T_{mean} \) is mean temperature of weld pool channel, which was taken as \( T_m + 300 \) (K), \( \lambda \) is thermal conductivity, and \( a \) is thermal diffusivity.

Method 3. The equation below was obtained by A.A. Lopatko and colleagues by formation of calculated ratios using Similarity and Dimensional Methods [3]. Then beam current can be written as follows:
\[ I = \frac{\lambda \cdot H \cdot T_m}{0.132 \cdot U} \cdot \left( \frac{2 \cdot v \cdot r}{a} \right)^{0.815} \cdot (1 + \frac{L_mm}{c \cdot T_m})^{0.815}. \]  

**Method 4.** Under these conditions, a mathematical model of a moving cylindrical heat source, which involves moving of a cylinder with constant surface temperature in an infinite plate [4], is interesting. The cylindrical heat source simulates the movement of vapor-gas channel during electron beam or laser welding. In this case channel surface temperature can be taken constant. By integrating heat flux through the surface of cylindrical source, it is possible to obtain full power of heat source moving at a speed \( v \). It can be written as follows:

\[ q = 2\pi H\lambda (T_s - T_0) \sum_{n=0}^{\infty} (-1)^n \varepsilon_n \frac{I_n \left( \frac{vd}{2a} \right)}{K_n \left( \frac{vd}{2a} \right)}, \]

where \( \lambda \) is metal thermal conductivity, \( T_0 \) is temperature at infinite distance from heat source; \( T_s \) is surface temperature of cylindrical source; \( v \) is speed of heat source movement; \( a \) is thermal diffusivity of the material being welded; \( d \) is diameter of cylindrical heat source; \( I_n \) and \( K_n \) are modified Bessel functions of \( n \)th order; \( \varepsilon_0 = 1 \) for \( n = 0 \), \( \varepsilon_n = 2 \), for \( n \geq 1 \).

Using full power of moving cylindrical source to determine beam power is possible if vapor-gas channel diameter is specified as cylindrical heat source and channel surface temperature is calculated from the condition of forces balance in the channel [5]. Using this method, change in the nature of heat transfer depending on welding speed and thermophysical properties of the material is considered, but costs on metal's melting and its partial evaporation are not taken into account.

To eliminate this drawback, a new method was developed on the base of this method. To determine heat source total power, in the equation (4) one component was added that takes into account heat consumption for metal melting and its partial evaporation. Then the equation (4) can be written as follows:

\[ q = 2\pi H\lambda (T_s - T_0) \sum_{n=0}^{\infty} (-1)^n \varepsilon_n \frac{I_n \left( \frac{vd}{2a} \right)}{K_n \left( \frac{vd}{2a} \right)} + Bhv\rho \left( L_m + \xi I_{\text{boil}} \right), \]

where \( \xi \) is evaporated metal part (in the calculations it was assumed to be equal 2%).

To determine energy costs for melting it is necessary to know weld width. It was explored using the same model of moving cylindrical heat source. For this purpose, distribution of temperature fields from such source with a constant surface temperature in polar coordinates was considered [6].

The isotherm \( T(r, \theta) = T_m \) is actually the boundary of weld pool (figure 1). The maximum width of weld pool is also weld width. Solving equation \( T(r, \theta) = T_m \) for \( r \), the dependence \( r(\theta) \) in polar coordinates was obtained. Then weld width can be determined by simultaneous solution of following equations:

\[ T_m = T_0 + (T_s - T_0) e^{\frac{vr \cos \theta}{2a}} \sum_{n=0}^{\infty} \varepsilon_n I_n \left( \frac{vr}{4a} \right) K_n \left( \frac{vr}{4a} \right) \cos(n\theta), \]

\[ \frac{dr}{d\theta} \cdot r = ctg(\pi - \theta), \]
\[ B = 2 \cdot r(0) \cdot \sin(\pi - 0) \, . \] (8)

**Figure 1.** Scheme for weld width determination in a case of cylindrical heat source moving.

For comparison calculated and experimental data, several tests were carried out on electron-beam welding plates. Plates with a thickness of 32 mm from 5V titanium alloy (Al = 4.7–6.3\%, Mo = 0.7–2\%, V = 1–1.9\%, Ti balanced), 27 mm from 40 Kh13 steel (C = 0.35–0.44\%, Cr = 12–14\%, Fe balanced) and 20 mm from D16 duralumin (Mn = 0.3–0.9\%, Cu = 3.8–4.9\%, Mg = 1.2–1.8\%, Al balanced) were used for experiments. Welding speed was changed in the range of 20…120 m/h. During complete fusion part of energy is lost on the screen installed on the back side of weld root and it is difficult to take into account its quantity. Therefore, during experiments absence of complete fusion was guaranteed and possibility of penetration depth measuring was maintained. For this purpose, beam current was selected experimentally, providing point penetration during sharp focusing, i.e. focusing current, which provides maximum penetration depth [7].

Then beam current was reduced by 5\% and plates were welded with different welding speeds. The ELA-151 power complex with accelerating voltage of 60 kV and maximum beam current of 650 mA was used for welding. The pressure in vacuum chamber was 10^{-3} mm of Hg.

### 3. Results of studies

Welding modes, on which samples from different alloys were welded, are presented in Table 2. Macrostructure of welded joints from 5V titanium alloy is shown in figure 2.

Figure 3 shows comparative results of experimental and calculated data, obtained using the developed method and existing methods. Since penetration depth is slightly varied at different welding speeds, for objective comparison of calculated and experimental data, the actual beam current was normalized to the penetration depth of 30 mm by a proportional change relative to the actual penetration depth. Using the proposed method, it is possible to calculate required electron beam power with satisfactory accuracy for various materials, whereas using existing methods it is possible to obtain results with acceptable accuracy only in a rather narrow range of welding speeds or only for some materials.

### 4. Discussion of studies results

Results of calculations according to method 1 are in poor agreement with experimental data, because in the calculations the same weld width and thermal efficiency set for all welding speeds. The accuracy of this method will increase significantly if these parameters known previously for various conditions. Acceptable results can be obtained using method 2 for titanium alloy and steel, especially at high speeds, but for duralumin calculated beam current exceeded real one by about 2 times. Method 3 can be considered unsuitable for titanium alloy and steel. An approximate regularity has been obtained for duralumin, but it is hardly suitable for practical use, especially at high speeds. The
Calculation results by method 4 show stably underestimated values of beam current, because energy costs for metal's melting and its evaporation are not taken into account.

**Table 2.** EBW modes ($I_{fakt}$ – actual beam current, $H_{fakt}$ – actual penetration depth, $I$ – corrected beam current value, calculated by proposed method)

| Material          | $U$ [kV] | $v$ [m/h] | $I_{fakt}$ [mA] | $H_{fakt}$ [mm] | $B_{mean}$ [mm] | $I$ [mA] | $H$ [mm] |
|-------------------|----------|-----------|-----------------|-----------------|-----------------|---------|---------|
| 5V titanium alloy | 20       | 100       | 29.4            | 2.68            | 102             |
|                   | 40       | 135       | 26.8            | 2.16            | 151             |
|                   | 60       | 170       | 28.1            | 1.79            | 181             | 30      |
|                   | 90       | 215       | 26.4            | 1.63            | 244             |
|                   | 120      | 250       | 27.7            | 1.43            | 270             |
| 40Kh13 steel      | 60       |           |                 |                 |                 |         |         |
|                   | 20       | 115       | 25.4            | 2.10            | 122             |
|                   | 60       | 200       | 24.8            | 1.52            | 217             | 27      |
|                   | 120      | 350       | 26.6            | 1.37            | 355             |
| D16 duralumin     | 20       | 65        | 17.1            | 2.34            | 76              |
|                   | 60       | 100       | 19.4            | 1.77            | 103             | 20      |
|                   | 120      | 140       | 16.0            | 1.90            | 175             |

*Figure 2.* Macrostructure of welded joints from 5V titanium alloy, obtained at different speeds: 120 (a), 90 (b), 60 (c), 40 (d) and 20 (e) m/h.

Using the developed method for determination required beam current and a program for mathematical calculations (for example, Mathcad), it is possible to obtain almost instantly a result with acceptable accuracy for practical use. However, this fact does not preclude the need of welding mode experimental verification, but it reduces the number of preliminary experiments up to one.

It is obvious that the developed method can be valid only for welding with deep penetration, when heat transfer along beam axis can be neglected. The disadvantages of this method also include the fact that characteristic widening of weld top, which in some cases can reach considerable sizes, is not taken into account. In addition, welding of metals with high thermal conductivity, such as aluminium and copper alloys, is characterized by formation of a weld with smooth increase of weld width from its root to its top part. For such alloys, the accuracy of welding modes determination by the developed method can be significantly lower.
Figure 3. Comparative results of experimental and calculated data, obtained using the developed method and existing methods.

5. Conclusions
Using the developed calculation method, it is possible to obtain required electron beam power during EBW of various materials (including complex alloys), depending on welding speed, diameter of vapour-gas channel and thermophysical properties and taking into account energy costs on metal melting and its partial evaporation.

It is established that in order to maintain a constant penetration depth, it is necessary to change electron beam power almost linear to welding speed.

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References
[1] Zuev I V 1998 Materials Processing by Concentrated Energy Flows (Moscow: MPEI) p 162
[2] Hashimoto T and Matsuda E 1964 J. Jap. Weld. Soc. 33(9) 38-46
[3] Lopatko A A, Kartashov G V, Tkachev L G et al. 1977 5th All-Union Conf. on Electron Beam Welding (Kiev: Naukova Dumka) p 16
[4] Arutyunyan R V, Bolshov L A, Vasilyev A D, Malyuta D D and Sebrant A Yu 1989 Effect of Laser Radiation on Materials (Moscow: Science) p 367
[5] Terentyev E V, Dragunov V K, Sliva A P and Scherbakov A V 2015 Welding International 29(2) 150–4
[6] Dragunov V K, Terentyev E V, Sliva A P, Goncharov A L and Marchenkov A Yu 2017 Welding International 31(4) 307–11
[7] Shcherbakov A V, Rodyakina R V, Kozhechenko A S, Gaponova D A, Goncharov A L, Dragunov V K 2017 Techn. Phys. Let. 43(11) 958–60.