Dependence of Weld Penetration Shape on Energy Efficiency in Electron Beam Welding Process

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Abstract. Investigation of relation between parameters of weld penetration shape and energy efficiency of electron beam welding process was performed in the paper. Analysis of welds cross sections of 316 L(N) steel weld joints obtained by the electron beam welding in the wide range of welding regimes is carried out. It is shown that the dependences of the thermal efficiency on the penetration area at different welding speeds are linear. According to the results, the thermal efficiency coefficient may exceed the ultimate theoretical value for linear heat source. Beam sweep does not affect essentially on the rate of thermal efficiency coefficient, since sweep application leads to an insignificant change in the area of the boundary of the weld pool with the base metal, and therefore, the amount of energy removed through this boundary also changes insignificantly and the penetration area remains almost constant.

1. Introduction
Since the appearance of electron beam welding (EBW), a large number of experimental and theoretical studies have been devoted to establishing the relationships between welding parameters and geometric characteristics of the weld [1-18]. Majority of researchers considered various thermal models in which penetration efficiency was determined mainly by the law of conservation of energy.

All parameters of the EBW process affect the shape and geometry of the weld, the main characteristics of which are the penetration depth and weld width. The heat input of electron beam welding is not a determining criterion for the quantitative assessment of the penetration process in contrast to arc welding methods [19], because at the same welding heat input value it is possible to obtain a different penetration depth. This phenomenon is caused by the peculiarity of dagger-shape penetration during EBW. The formation of the weld depends not only on the thermal power of the source, but also on the power density [4]. With the same source power, its specific power can be distributed on the heated surface in different ways, because the power density depends on the focusing current, the distance between the welding gun and the object as well as the type of the beam sweep. Oscillation of the beam and its sweep along various trajectories with a high frequency is a flexible technique for controlling the power density in the processing zone [20].

The relationship of the EBW parameters with the characteristics of the penetration zone for the momentary volume of molten metal according to the model [5] has the form:

$$V_w \cdot F_m = \eta_t \cdot q_{eff} \cdot S_m,$$

(1)
where \( V_w \) - welding speed, m/s; \( F_m \) - cross-sectional melt area, \( \text{m}^2 \); \( \eta_t \) - thermal efficiency; \( q_{eff} \) - effective power of the source, which reaches the heated surface, W; \( S_m \) - heat capacity corresponding to the melting temperature, \( \text{J/m}^3 \).

Effective power is estimated by the formula:

\[
q_{eff} = I_b \cdot U_{acc} \cdot \eta_{eff} \tag{2}
\]

where \( I_b \) - beam current, mA; \( U_{acc} \) - accelerating voltage, kV; \( \eta_{eff} \) - efficiency, taking into account the loss of kinetic energy of electrons during its transition to heat energy.

The volumetric heat capacity when the metal is heated from room temperature to the melting point, is determined by the expression:

\[
S_m = \rho \cdot \left( c \cdot \Delta T_m + L_m \right) \tag{3}
\]

where \( \rho \) - metal density, \( \text{kg/m}^3 \); \( c \) - specific heat capacity of metal, \( \text{J/(kg·°C)} \); \( \Delta T_m = T_m - T_0 \) - increase from the initial temperature \( T_0 \) to the melting point, \( °C \); \( L_m \) - specific heat of fusion, \( \text{J/kg} \).

The cross-sectional area of the weld is determined by equation:

\[
F_m = B \cdot H \tag{4}
\]

where \( B \) - average weld width, m; \( H \) - penetration depth, m.

The average weld width during welding in continuous mode is found from the ratio:

\[
B = \frac{4 \cdot d \cdot q_{eff} \cdot \eta_t}{\pi \cdot S_m \cdot H \cdot V_w} \tag{5}
\]

where \( d \) - beam diameter, m.

The average width is determined at the level of \( H/e \). The beam diameter is defined by the equation:

\[
d = \frac{4 \cdot q_{eff}}{\pi \cdot H \cdot V_w \cdot S_{ev}} \tag{6}
\]

where \( S_{ev} \) - heat capacity corresponding to the evaporation temperature, \( \text{J/cm}^3 \).

The volumetric heat capacity of evaporation is expressed:

\[
S_{ev} = \rho \cdot \left( c \cdot \Delta T_{ev} + L_{ev} \right) \tag{7}
\]

Where \( \Delta T_{ev} = T_{ev} - T_0 \) - increase from the initial temperature to the temperature of evaporation (boiling), \( °C \); \( L_{ev} \) - specific temperature of evaporation, \( \text{J/kg} \).

The thermal efficiency of penetration is mainly determined by the energy conversion efficiency, which, in turn, depends on various factors: the source power, welding speed, type of welded structure and thermal properties of the materials being welded. The thermal efficiency of base metal penetration is determined by the ratio between heat capacity of the base metal melted per unit time and the effective power of the electron beam, i.e. thermal efficiency expresses the share of power that directed to the metal melting. The rest part of the energy aimed at heat removing by the mechanism of thermal conductivity without its melting [4]. For a linear heat source in a plate [4], the value of thermal efficiency increases with a growth in the dimensionless criterion, which can be found by the formula:

\[
e_2 = \frac{q}{\delta \cdot a \cdot \rho \cdot h_m} \tag{8}
\]

where \( \delta \) - thickness of the welded plate, m; \( a \) - coefficient of thermal diffusivity, \( \text{m}^2/\text{s} \); \( h_m \) - heat capacity, \( \text{J/kg} \).

According to this model, the value of the theoretical efficiency cannot exceed 0.484 in the case of extremely powerful linear heat sources.
Currently, there is no single method for determining the welding mode due to the complexity and instability of the processes taking place in the vapor-gas channel, as well as the difference in the characteristics of the welding guns and power sources. All formulas characterize only the relationship between the EBW parameters and the penetration geometry.

The main aim of the study is to establish a ratio between characteristics of the penetration shape and energy efficiency of the EBW and determine the values of thermal efficiency under various parameters and regimes of deep penetration welding.

2. Equipment and research technique
The research was based on the data obtained during EBW on the ELA 60/60 electron-beam machine, developed by the Paton Electric Welding Institute (Ukraine) and ELA-40I developed by JSC “NITI Progress” (Russia). Accelerating voltage during all experiments was 60 kV; beam current varied from 100 to 780 mA; welding speed changed from 15 to 200 m/h. The material under study was AISI 316L(N) steel.

The calculation of the welding mode parameters for circular welds and plates was done in MATHCAD and Microsoft Excel programs with accordance to formulas 1-7. The values of thermal constants for stainless steel were used during estimation of the heat capacity corresponding to the melting temperature \( S_m = 8.915 \, \text{J/mm}^3 \); the heat capacity corresponding to the evaporation temperature \( S_{ev} = 60.88 \, \text{J/mm}^3 \).

Thermal efficiency was computed from formula (1), taking as a basis the parameters of the welding mode:

\[
\eta_t = \frac{V_w \cdot F_m \cdot S_m}{\eta_{eff} \cdot I_b \cdot U_{acc}}.
\]

Area \( F \) and penetration depth \( H \) were found using WeldShape software. The beam diameter \( d \) was determined by formula (6).

The initial data for the calculation were: the accelerating voltage \( U_{acc} = 60 \, \text{kV} \); efficiency \( \eta_{eff} = 0.95 \). All calculations and measurements were performed on macrosections. The data of 48 macrosections used in analysis. Those specimens were obtained with no full penetration during welding in the lower position. Other specimens obtained by the full penetration mode were excluded from 70 processed macrosections, because for them the effective power \( q_{eff} \) could not be determined precisely.

3. Results and discussion
Several welded joints macrosections are shown in figure 1. The results of measurements and calculations are presented in the table 1.
Table 1. Results of calculating the penetration area for various EBW modes.

| No. | Welding speed $V_w$, m/h | Beam current $I_b$, mA | Focusing current $I_f$, mA | Beam diameter $d$, mm | Penetration area $F_{pen}$, mm² | Thermal efficiency $\eta_t$ | Weld depth $H$, mm | Weld width $B$, mm | Weld shape factor, $H/B$ |
|-----|------------------------|------------------------|---------------------------|-----------------------|-------------------------------|--------------------------|------------------|-----------------|-----------------|
| 1   | 30                     | 169                    | 620                       | 1.084                 | 54.649                        | 0.421                    | 22.312           | 1.838           | 12.142          |
| 2   | 30                     | 172                    | 610                       | 1.034                 | 61.116                        | 0.463                    | 23.802           | 1.838           | 12.948          |
| 12  | 30                     | 183                    | 630                       | 1.236                 | 63.778                        | 0.454                    | 21.177           | 2.176           | 9.731           |
| 18  | 30                     | 202                    | 620                       | 1.417                 | 77.943                        | 0.503                    | 20.387           | 2.626           | 7.764           |
| 20  | 100                    | 120                    | 966                       | 0.706                 | 9.686                         | 0.351                    | 7.294            | 1.093           | 6.673           |
| 22  | 100                    | 170                    | 966                       | 0.754                 | 15.339                        | 0.392                    | 9.677            | 1.233           | 7.845           |
| 24  | 100                    | 190                    | 970                       | 0.676                 | 18.010                        | 0.412                    | 12.062           | 1.134           | 10.638          |
| 39  | 100                    | 105                    | 958                       | 0.592                 | 16.429                        | 0.680                    | 7.617            | 1.275           | 5.973           |
| 41  | 100                    | 100                    | 957                       | 0.446                 | 13.058                        | 0.567                    | 9.630            | 0.877           | 10.978          |
| 43  | 100                    | 100                    | 940                       | 0.641                 | 12.864                        | 0.559                    | 6.692            | 1.253           | 5.343           |
| 49  | 100                    | 100                    | 965                       | 0.769                 | 8.752                         | 0.380                    | 5.579            | 1.239           | 4.503           |
| 51  | 100                    | 100                    | 958                       | 0.404                 | 11.652                        | 0.506                    | 10.618           | 0.751           | 14.137          |
| 53  | 15                     | 780                    | 740                       | 2.592                 | 417.454                       | 0.349                    | 86.104           | 4.001           | 21.521          |
| 55  | 15                     | 780                    | 750                       | 2.667                 | 389.082                       | 0.325                    | 83.685           | 3.973           | 21.066          |
| 58  | 15                     | 780                    | 760                       | 2.690                 | 382.413                       | 0.320                    | 82.949           | 3.976           | 20.861          |
| 60  | 15                     | 780                    | 760                       | 2.582                 | 449.210                       | 0.375                    | 86.433           | 4.131           | 20.921          |
| 66  | 15                     | 780                    | 780                       | 2.570                 | 515.489                       | 0.431                    | 86.838           | 4.408           | 19.698          |
| 71  | 35                     | 100                    | 942                       | 1.408                 | 18.037                        | 0.274                    | 8.709            | 1.926           | 4.522           |
| 74  | 35                     | 125                    | 932                       | 1.501                 | 28.312                        | 0.344                    | 10.214           | 2.300           | 4.441           |

Experimental results show that the maximum efficiency factor obtained during welding is 0.68. For seven macrosections the thermal efficiency exceeded 0.484 which is 14.6% of the total number of specimens. When plotting the graphs, the values of the mean thermal efficiency for each mode were used. This feature is explained by fluctuations in the penetration depth.

Figure 2 shows the dependence of the thermal efficiency on the weld shape factor $H/B$. The approximation of the experimental points by a parabolic function shows that the maximum of the approximated value of the thermal efficiency is close to the maximum theoretical and corresponds to a weld shape factor of about 15. For various investigated modes, the value of thermal efficiency ranges from 0.274 to 0.680 (Table 2).

The efficiency versus the amount of energy per unit area is shown in Figure 3. The approximation of the experimental results by a linear function contradicts the data presented in [6]. It means that for certain welding conditions, the use of a linear heat source model to describe the EBW process gives low values of thermal efficiency.

The dependences of the thermal efficiency on the penetration area at various welding speeds are shown in figure 4. These dependences are linear, thus for a constant welding speed in a wide range of electron beam power, the thermal efficiency is inversely proportional to the welding heat input and expression (9) is valid.

The beam sweep does not affect noticeably on the value of the thermal efficiency (figure 5); in both cases a parabolic dependence is observed. The use of a beam sweep along a circular path leads to a change in the shape of the weld and does not significantly affect the value of the thermal efficiency. Apparently, it can be justified by the fact that the beam sweep causes a slight change in the area of the
border between weld pool and base metal. As a result, the value of the energy removed through this border also changes negligibly, while the penetration area remains practically constant.

Table 2. The results of determining the thermal efficiency in the investigated modes of EBW.

| No. | Thermal efficiency $\eta_t$ | Weld depth $H$, mm | Weld width $B$, mm | Weld shape factor, $H/B$ |
|-----|-----------------------------|-------------------|-------------------|------------------------|
| 1   | 0.421                       | 22.312            | 1.838             | 12.142                 |
| 2   | 0.463                       | 23.802            | 1.838             | 12.948                 |
| 12  | 0.454                       | 21.177            | 2.176             | 9.731                  |
| 18  | 0.503                       | 20.387            | 2.626             | 7.764                  |
| 20  | 0.351                       | 7.294             | 1.093             | 6.673                  |
| 22  | 0.392                       | 9.677             | 1.233             | 7.845                  |
| 24  | 0.412                       | 12.062            | 1.134             | 10.638                 |
| 39  | 0.680                       | 7.617             | 1.275             | 5.973                  |
| 41  | 0.567                       | 9.630             | 0.877             | 10.978                 |
| 43  | 0.559                       | 6.692             | 1.253             | 5.343                  |
| 49  | 0.380                       | 5.579             | 1.239             | 4.503                  |
| 51  | 0.506                       | 10.618            | 0.751             | 14.137                 |
| 53  | 0.349                       | 86.104            | 4.001             | 21.521                 |
| 55  | 0.325                       | 83.685            | 3.973             | 21.066                 |
| 58  | 0.320                       | 82.949            | 3.976             | 20.861                 |
| 60  | 0.375                       | 86.433            | 4.131             | 20.921                 |
| 66  | 0.431                       | 86.838            | 4.408             | 19.698                 |
| 71  | 0.274                       | 8.709             | 1.926             | 4.522                  |
| 74  | 0.344                       | 10.214            | 2.300             | 4.441                  |

Figure 2. Dependence of thermal efficiency $\eta_t$ on the weld shape factor $H/B$.

Figure 3. Dependence of thermal efficiency $\eta_t$ on the amount of energy per unit area.

4. Conclusions

1. The results of the experiments make possible to confirm that the values of the thermal efficiency for EBW can significantly exceed the theoretical values of the efficiency factor for a linear heat source. The maximum value of thermal efficiency was obtained by an EBW of 316L(N) steel with a thickness of 8 mm at a speed of 100 m/h and accounted for 0.68.

2. Changing the shape of penetration during welding with the deep penetration mode using a beam sweep along a circular trajectory does not significantly affect the efficiency of the EBW process.
Figure 4. Dependences of thermal efficiency $\eta_t$ on the penetration area: 1 – welding speed of 100 m/h; 2 – welding speed of 35 m/h; 3 - welding speed of 30 m/h.

Figure 5. Dependence of thermal efficiency $\eta_t$ on the weld shape factor $H/B$: 1 – with a beam sweep; 2 – no beam sweep.

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