Effect of Welding Speed on Electron Beam Welding Thermal Efficiency

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Abstract. The results of thermal efficiency evaluation during electron beam welding of alloys with different thermophysical properties in the range of welding speeds from 20 m/h to 120 m/h are presented. It was shown that the thermal efficiency increased in accordance with the rising welding speed. Also, the thermal efficiency greatly depends on the thermal conductivity: the lower the thermal conductivity, the higher the thermal efficiency. Thus, with an increase in welding speed from 20 m/h to 120 m/h, the thermal efficiency grew steadily for all three considered types of alloys: values for a titanium alloy 5V went up from 54% to 67%, while for the steel 40Kh13 values rose from 46% to 63% and the most significant increment related to duralumin D16, the thermal efficiency for this alloy increased from 18% to 40%. The equation which established the ratio between the thermal efficiency, welding speed and thermal conductivity for electron beam welding with full penetration was derived.

1. Introduction
One of the most important parameters of welding modes is the thermal efficiency $\eta_T$. This parameter is used for preliminary calculations of welding modes [1–3] and evaluation of thermal energy efficiency during welding. It is known [1–3] that the thermal efficiency depends substantially on thermophysical properties of the material, the welding speed and parameters of the heat source.

Both empirical and theoretical methods for determining thermal efficiency were described in literature. The paper [3] often provides the thermal efficiency value for a fast-moving linear heat source, which is equal to 48.4% as the maximum possible at the infinite welding speed, while the experimental thermal efficiency values in some cases exceed 50% [4, 5]. Analysis of cylindrical and flat heat sources models interprets the realization of the thermal efficiency more than 90% [6, 7].

The following equation [3] is generally used for the experimental determination of $\eta_T$:

$$\eta_T = v \cdot F_w \cdot \frac{S_m}{q_{eff}}$$

(1)

where $v$ – welding speed; $F_w$ – cross-sectional area of the weld joint; $S_m$ – enthalpy of the metal at the melting temperature; $q_{eff}$ – effective beam power.

In [8] it is proposed to approximate the dependence of the penetration depth on the speed and on the beam power for electron-beam welding (EBW) by the following equation:

\[ D = k \cdot v \]
\[ \eta_{f} = \frac{s_{m} \cdot \pi \cdot d}{4} \left( \frac{A_1}{(q_{\text{eff}} / v)^{2}} + \frac{A_2}{q_{\text{eff}} / v} + A_3 \right), \]  

(2)

where \( A_1, A_2 \) and \( A_3 \) – empirical coefficients that are determined in the paper on a large number of experimental data in the beam power range from 1 to 8 kW and welding speed from 3.6 to 28.8 m/h.

However, this formula characterizes only the dependence on the linear energy \( q_{\text{eff}}/v \) and does not directly connected with the welding speed. It can lead to dramatic errors, since the same treatment \( q_{\text{eff}}/v \) can be obtained within wide limits of welding speeds.

According to [9], where experimental effect of thermal efficiency on welding speed is presented, the thermal efficiency values reach a maximum at welding speed near 15-20 m/h. The increase in thermal efficiency is explained by the fact that with a growth in the welding speed, the proportion of heat factor spent on heating the base metal decreases; and the decline in efficiency after reaching the peak is due to the fact that the weld joint width becomes thinner than the diameter of the heat source and the peripheral zone of the beam spends energy only on heating the heat affected zone (HAZ). Such dependence of thermal efficiency on welding speed can be formed by welding with a low concentration of power density and large diameters of the heat source. In such conditions of electron beam welding with full penetration, when the beam diameter is less than 1 mm, such parameter distribution is unlikely.

Therefore, currently in the scientific and technical literature there is insufficient experimental data on the effect of welding speed on the thermal efficiency during EBW with full penetration. That is why, the purpose of this study is to obtain experimental dependencies of thermal efficiency on the EBW speed for materials with various thermophysical properties.

2. Methodology

Welded joints specimens of titanium alloy 5V, steel 40Kh13 and duralumin D16, which were obtained by EBW without full penetration were used to determine thermal efficiency. The technology of their production is described in [10]. Welding modes are shown in Table 1. The thickness of the plates to be welded was 32 mm, 27 mm and 20 mm respectively.

Estimation of thermal efficiency according to experimental data was done by the formula (1). Three microsections were made from each weld joint. The cross-sectional areas of weld joints \( F_{\text{w}} \) on the etched microsections were determined by an Observer Z1m microscope from Carl Zeiss. Panoramic pictures were made using standard AxioVision software and then the cross-sectional area of the weld joint was obtained by contouring the weld joint profile.

| Material                  | Accelerating voltage \( U \), kV | Welding speed \( v \), m/h | Beam current \( I \), mA | Penetration depth \( H \), mm | Weld width \( B_{w} \), mm |
|---------------------------|----------------------------------|----------------------------|--------------------------|----------------------------|--------------------------|
| 5V titanium alloy         | 60                               | 20                         | 100                      | 29.4                      | 2.68                     |
|                           |                                  | 40                         | 135                      | 26.8                      | 2.16                     |
|                           |                                  | 60                         | 170                      | 28.1                      | 1.79                     |
|                           |                                  | 90                         | 215                      | 26.4                      | 1.63                     |
|                           |                                  | 120                        | 250                      | 27.7                      | 1.43                     |
| 40Kh13 steel              | 60                               | 20                         | 115                      | 25.4                      | 2.10                     |
|                           |                                  | 60                         | 200                      | 24.8                      | 1.52                     |
|                           |                                  | 120                        | 350                      | 26.6                      | 1.37                     |
| D16 aluminum alloy        |                                  | 20                         | 65                       | 17.1                      | 2.34                     |
|                           |                                  | 60                         | 100                      | 19.4                      | 1.77                     |
|                           |                                  | 120                        | 140                      | 16.0                      | 1.90                     |

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The heat factor of the melt metal at the melting temperature $S_m$ was defined as the sum of the integral of the dependence of the specific heat capacity on the temperature and the specific heat of melting. For 5V and D16 alloys no dependencies of specific heat capacity on temperature is represented in open-source literature. Therefore, taking into account the identity of heat capacity values for pure metals and their alloys at a room temperature, data for pure titanium and aluminium were used in calculations [11, 12]. The dependence of specific heat capacity on temperature is given only up to 1073 K for steel 40Kh13 [13], thus, in such cases the data for pure iron were used [14]. The effect of specific heat capacity on temperature for different types of metals which was used in calculations are shown in figure 1.

![Figure 1. Dependency of specific heat capacity of materials on temperature.](image)

There are no values of the specific heat of fusion were found in the scientific and technical literature for the alloys under consideration, so values for pure metals were used in the calculations. The values of the physical properties of the metal used in the calculations are presented in Table 2.

| Properties                        | 5V     | 40Kh13 | D16     |
|-----------------------------------|--------|--------|---------|
| Density $\rho$, kg/m³ at 300 K    | 4500 [12] | 7870 [12] | 2697 [12] |
| Specific thermal capacity $c$, J/kg*K at 300 K | 530.8 [11] for Ti | 452 [13] for Fe | 883 [15] for Al |
| Specific heat of melting $L_m$, J/kg | 470 000 [16] for Ti | 270 000 [16] for Fe | 393 000 [16] for Al |
| Melting temperature $T_m$, K      | 1 944 [17] for Ti | 1 773 [17] for Ti | 775 (solidus) [17] |

The effective beam power was determined by the formula:

$$q_{eff} = U \cdot I \cdot \eta_{eff}$$

(3)

where $U$ – accelerating voltage; $I$ – beam current; $\eta_{eff}$ – efficiency of the electron beam, which is equaled to 95%.

Thus, thermal efficiency was estimated for each microsection based on the weld area sizes.
3. Results of the research

Results of thermal efficiency determination by experimental method are shown in Figure 2 by charts. As can be seen from the charts, the thermal efficiency is highly dependent on both material properties and welding speed. Thus, the maximum value $\eta_T = 67\%$ was obtained for the titanium alloy 5V at $v = 120$ m/h and the minimum value equaled to $\eta_T = 18\%$ for the aluminum alloy at $v = 20$ m/h. It should be noted that the thermal efficiency increases gradually with rising welding speed and the peak registered in paper [3] was not observed.

![Figure 2](image-url)  
**Figure 2.** Dependence of thermal efficiency on welding speed for different materials.

4. Discussion of results

The presence of a maximum on the dependence of thermal efficiency on the welding speed depends on the distribution of the power density over the beam section. Thereby, during welding with a well-focused narrow beam almost all the power is spent on heating the welding bath, while when welding with a distributed heat source with an increase in the welding speed, a part of the beam power at the periphery will be spent on heating the base metal, thereby reducing the efficiency [9]. Thus, for the EBW with full penetration the thermal efficiency increases continuously with rising welding speed, provided that the diameter of the beam remains smaller than the weld width.

Apparently, at the most commonly used EBW speeds it is difficult to achieve the thermal efficiency to a value of 90%, whereas the theoretical value of which is published in papers [6, 7]. At the same time, it is obvious that the model of the linear heat source [18] also does not accurately reflect the energy balance character at EBW, especially at high welding speeds. It is associated with a multiple overestimation of temperature near the linear source area [19]. Therefore, existing analytical models of thermal processes during welding do not allow to make a precise assessment of the EBW thermal efficiency.

The analysis of the charts in Figure 2 shows that the higher the thermal conductivity of the material, the lower the thermal efficiency. The coefficient of thermal conductivity compared to the welding speed affects the thermal efficiency in the opposite way. Plotting the dependence of thermal efficiency on the ratio of the welding speed to the coefficient of thermal conductivity $v/a$ (Figure 3) shows that the obtained results of thermal conductivity for all materials can be described by a single logarithmic ratio:

$$ q_{eff} = A \cdot \ln \left( \frac{v}{a} \right) - B, \quad (4) $$

where $A$ and $B$ – empirical coefficients, $a$ – thermal conductivity.
Figure 3. Dependence of thermal efficiency on ratio of welding speed to thermal conductivity coefficient.

Provided that the welding speed has a dimension of m/s and a thermal conductivity coefficient of m²/s, the approximation of the results obtained in this work allows to estimate the following coefficients:

\[ A = 0.1263 \]
\[ B = 0.3852 \]

In this case, the correlation ratio was \( R^2 = 0.9015 \). Certainly, to get more accurate coefficient, more experimental thermal efficiency data for EBW materials with different thermophysical properties should be performed. However, the obtained equation allows to make a satisfactory estimation of the thermal efficiency of the EBW process with full penetration based on welding speed and thermal conductivity coefficient.

The main factors that reduce the accuracy of determining thermal efficiency by an experimental method should also be mentioned. Firstly, there is a lack of data concerning thermophysical properties of industrial alloys, that is why we have to use approximate dependencies of specific heat capacity on temperature, to use data on latent melting heat for pure metals, not to take into account latent heat of phase transformations in a solid state for polymorphic metals. Secondly, the effective efficiency in the calculation was 95%, although its value may differ significantly depending on the EBW modes and external conditions. When elaborating the coefficients in equation (4), the main problem is the dependence of the thermal conductivity coefficient on the temperature and structure of the alloy.

5. Conclusions
It has been found that during EBW with full penetration the thermal efficiency increases gradually for all alloys under study. Thus, with an increase in welding speed from 20 m/h to 120 m/h, the thermal efficiency grew steadily for all three considered types of alloys: values for a titanium alloy 5V went up from 54% to 67%, while for the steel 40Kh13 values rose from 46% to 63% and the most significant increment related to duralumin D16, the thermal efficiency for this alloy increased from 18% to 40%.

Increasing the thermal conductivity of alloys leads to a decrease in thermal efficiency.

The equation which establishes for EBW with full penetration the relationship between thermal efficiency, welding speed and thermal conductivity has been proposed.
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