Investigation of the optimal modes of electron-beam wire deposition

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Abstract. The paper is devoted to the definition of the minimum electron beam power that is required to obtain stable layer formations during the additive electron beam wire deposition. Correlation between the minimum energy that is needed for stable deposition and the deposition speed has been established. Additionally, the influence of the electron beam oscillation type on geometrical parameters of single layers have been investigated.

1. Introduction
Current research in the field of electron beam metal wire technologies pays special attention to the structure and properties of the products made of titanium [1, 2], nickel [3, 4] aluminum alloys [5], and stainless steel [6, 7]. Also, heat and mass transfer models of wire deposition process were investigated [8]. However, in these studies the technological aspects of the process are not considered. They lack attention to the selection of the main parameters of additive electron beam wire deposition such as the electron beam power, feed rate, deposition rate, oscillation type and its parameters and their influence on the parameters of deposited layers and products.

The development of the technological basis for manufacturing of components with complicated shape includes determining relations between deposition process parameters, layers geometry, their structure and properties for obtaining the required wall thickness and metal structure. It is necessary to define the criteria that limit the value range of deposition process parameters and allow to obtain the product with the needed shape and properties. To limit the range of parameters it is advisable to determine the minimal values of the electron beam power under which the stability of deposition is saved.

The purpose of this research was to determine the electron beam power required to ensure the stable formation of beads at different feed rates and deposition speeds, and to investigate the influence of the beam oscillation type on the geometrical parameters of beads.

2. Research methods
The process of electron beam wire deposition was carried out using an electron-beam machine with an accelerating voltage of 60 kV that was equipped with an automatic wire feeder.

The determination of the minimal electron beam power required to ensure the stable formation of a single layer at different wire feed rates and surfacing rates was divided into two stages.

The first stage was to establish the minimum electron beam power required for melting the feeding wire. The investigation was conducted using wires of various materials: stainless austenitic steel AISI
316L, Fe-Ni alloy 36NKhTU (36% Ni, 12% Cr, 3% Ti, 1% Al, Fe balanced) and titanium alloy 2V (2% Al, 1.5% V, Ti balanced). The feed rate varied in the range of 1.0–3.0 m/min with a step of 0.5 m/min. The beam oscillation represented a circle with the diameter equal to half of the wire diameter. The frequency of the oscillation was 500 Hz.

The second stage involved the determination of the minimum beam power that ensured the stable formation of the layer. The investigation consisted of deposition of the 316L steel wire with the diameter of 1.2 mm on a substrate of the same material at different feed and deposition rates (Table 1). The wire was fed into the melting front of a liquid pool (Figure 1). The electron beam oscillation of type "sawtooth to crystallization front" was used with the length of 1 mm during these experiments.

The selection of the oscillation type is based on the hypothesis that this type of oscillation can lead to height increase of deposited layer. The electron beam movement cycle during the oscillation consists of two parts: the translation along the longitudinal axis and the rapid displacement to the beginning of oscillation trajectory (Figure 2). It is known that the use of the sawtooth oscillation in the process of electron beam welding results in intensification of liquid metal transfer to a rear part of the liquid pool and in metal displacement from the root to the top of a joint [9]. This effect can be used in additive electron beam wire deposition.

![Figure 1. Feeding the wire in the deposition process.](image1)

![Figure 2. Movement of the electron beam with the use of sawtooth oscillation](image2)

| Wire feed rate $V_f$ (m/min) | Deposition rate $V_d$ (m/h) |
|-----------------------------|---------------------------|
|                             | 15       | 30       | 45       |
| 1.0                         | ×        | ×        | ×        |
| 2.0                         | ×        | ×        | ×        |
| 3.0                         | ×        | ×        | ×        |

Table 1. Combination of wire feed rate and deposition rate

The influence of the application of different types of electron beam oscillation on the single layer beads geometry was investigated via deposition using the wire with the diameter of 1.2 mm which was made of steel 316L. The deposition process was carried out with the feed rate of 2 m/min and the deposition rate of 30 m/h. The beam current was 16 mA. The oscillation types "sawtooth to crystallization front", "sinusoidal", "zigzag", and "circle" were used (Figure 3). Also, the comparison of deposition with and without the oscillation was done. $X$ axis of the oscillation was oriented along the wire feed direction. The oscillation parameters are shown in Table 2.

In order to compare geometrical parameters of the beads cross-sections were made. The analysis of the geometry was conducted using an optical microscope Zeiss Observer Z1.
Figure 3. Trajectory of the electron beam movement using different types of oscillation: (A) sinusoidal, (B) zigzag, (C) circle.

Table 2. Geometric parameters of the oscillations

| Oscillation type | Dimensions | Frequency f (Hz) |
|------------------|------------|-----------------|
| Sawtooth         | Length $A_x$ (mm): 1 | Width $A_y$ (mm): 0 | 100 |
|                  | Length $A_x$ (mm): 1 | Width $A_y$ (mm): 0.6 | 100 |
| Zigzag           | Length $A_x$ (mm): 1 | Width $A_y$ (mm): 0.6 | 100 |
| Sinusoidal       | Length $A_x$ (mm): 0.6 | Width $A_y$ (mm): 0.6 | 500 |
| Circle           | Length $A_x$ (mm): 0.6 | Width $A_y$ (mm): 0.6 | 500 |

3. Results

It was shown that the minimal electron beam power required to melt the wire that is fed with different rates is linearly related to the feed rate (Figure 4).

The minimum power required to melt a wire is the power below which the wire is melting incompletely. The minimum power could be presented as follows:

$$ q = V_f \cdot F \cdot S_m $$

where $V_f$ – wire feed rate, m/s, $F$ – wire cross-section area, m$^2$, $S_m$ – enthalpy of liquid metal at the melting point, J/m$^3$.

Thus, the tilt angle of the graph equals numerically to energy per volume required to melt the wire and depends on the thermophysical properties of any material. Energy per volume equals the enthalpy of liquid metal in this case. The effective electron beam power can be determined as:

$$ q_{ef} = n_{ef} \cdot U \cdot I $$

where $n_{ef}$ – beam heating efficiency equal to 0.95, $U$ – accelerating voltage, V, $I$ – beam current, A.

Figure 4. Relation between electron beam energy that is needed to melt the wires of different materials and wire volume that is fed per unit of time. Diameter of the wires of 316L and 36NKhTU – 1.2 mm, and 2V – 1.6 mm.
During the process of wire melting some part of electron beam power is spent on losses which connected with the overheating of liquid metal and radiation. The thermal efficiency of melting a wire $\eta_t$ is defined as the ratio of spent electron beam energy (2) to the power needed to turn solid metal of wire to liquid metal (1).

Considering the dependence of thermophysical properties of stainless steel 316L on temperature [10], the thermal efficiency $\eta_t$ of deposition process is close to the value of 1 (table 3). At the feed rate of 1 m/min the melting of the wire took place with the formation of big metal droplets. Decreasing $\eta_t$ is connected with beam energy input both into wire melting and overheating the droplet.

**Table 3.** Thermal efficiency $\eta_t$ of melting the wire of 316L, minimum beam power $q$ vor various values of feed rate $V_f$

| $V_f$ (mm/min) | $\eta_t$ | $q$ (W) |
|----------------|----------|---------|
| 1.0            | 0.867    | 239     |
| 1.5            | 0.975    | 319     |
| 2.0            | 0.971    | 427     |
| 2.5            | 0.958    | 542     |
| 3.0            | 0.975    | 638     |

During the process of deposition, electron beam energy is distributed between melting the wire and melting the substrate. To ensure the stable layer formation it is required to sustain the melting of the substrate for creating a joint liquid pool. Decreasing the electron beam power in the process of deposition has resulted at some point in the change of the stable deposition into the formation of droplets (figure 5). This effect relates to the lack of energy input to melt the substrate. The electron beam power below which occurs a shift from the layer formation to the droplets is the minimum for obtaining stable layers.

**Figure 5.** Changing the type of deposition as a result of decreasing the electron beam power. Deposition parameters: 1 - $V_f = 3$ m/min, $V_d = 15$ m/h; 2 - $V_f = 2$ m/min, $V_d = 45$ m/h; 3 - $V_f = 3$ m/min, $V_d = 30$ m/h.

As a result of layer deposition investigation with the decline of the beam power it was determined that the minimum energy per wire volume $q/V_f F$ which is required for sustaining stable process relates linearly to the deposition rate (Figure 6). This relation makes it possible to define the limit value of energy per volume below which layer formation will be unstable or interrupted. The horizontal dotted line corresponds to energy per volume that is required to melt the wire of 316L without deposition. The line divides the area below the graph into two parts. The upper part between the graph and the dotted line corresponds to the energy per volume required to melt the substrate, and the lower part to wire melting.
Figure 6. Relation between the minimum energy per volume \((q/V_d F)\) required to stable deposition and deposition rate \(V_d\).

It is possible to adjust geometrical parameters of the layers in different ways. The main method consists of regulating feed and deposition rates. In this case the layer size changes without changing the form. It is possible to change the layers form using electron beam oscillation. The comparison of geometrical parameters of deposited layers, obtained with the same electron beam power, feed and deposition rates, but different types of oscillation (Figure 7), made it possible to establish the impact of the oscillation type on the layer height.

The oscillations can be divided into 2 types. The first type includes the oscillations types that do not impact on the movement of liquid metal from the melting front to the crystallization front. This includes oscillation types like circle, concentric circles, and ellipses. The second type includes oscillations that intensify the transfer of liquid metal to the crystallization area. Oscillation types "sawtooth", "sinusoidal" and "zigzag" belong to this group. The movement of electron beam with the use of the second type oscillations leads to the displacement of liquid metal on to crystallized layer. This effect results in the increase of the layer height.

Figure 7. Cross-section of the single layers, deposited with different type of oscillation.

The height of the beads which were deposited with the use of "sawtooth", "sinusoidal", and "zigzag" oscillations is greater than the height of beads deposited with the use of circle or without oscillation at all due to the above-mentioned effect (Figure 8). The layer that was made with "zigzag" is the highest and has the biggest relation of height to average width \((B_a = F_{dep}/H)\), probably due to the beam power density distribution that was proportional to the width of the wire. The beam power is mostly concentrated in axis of the wire and decreases at the edges.

The application of oscillations allows to redistribute the electron beam power density on the surface of the substrate. It is possible to adjust the width of the layers in a certain range due to the regulation the width of the oscillation \(A_y\). To obtain the thinnest layers it is advisable to decrease the width of the oscillation to 0. Thus, the transverse size of heating source becomes equal to the size of the beam focused on the surface of the substrate.
Figure 8. Changing of height, average width, and relation of height to average width \((H/B_a)\) depending on oscillation type.

However, it is shown that the relation of the average width to the layer’s height allowed to establish that the oscillations with the width equal to the half of wire diameter or lower do not impact on the width of the layer. In this case, the main parameters leading to the change of the layer width are feed and deposition rates.

4. Conclusions
The investigation of wire melting with the use of the electron beam showed that the thermal efficiency of the wire melting equals to 0.867 with the feed rate of 1 m/min. If the feed rate is more than 1.5 m/min then the thermal efficiency is constant and does not drop below 0.95. It is not advisable to carry out the process using low feed rates because a large proportion of beam energy is wasted on overheating the liquid droplets. The minimum energy per volume \(q/V_f\) that is needed to sustain stable deposition process grows proportionally to the deposition rate and does not depend on the feed rate. The application of oscillations like "sinusoidal", "sawtooth" and "zigzag" that intensify liquid metal transfer in the liquid pool, leads to the increase of the layers height as the beam movement during the oscillations displaces liquid metal to crystallized bead. As a result of the effect, the bead with the biggest relation of height to average width is obtained, as compared to the beads that are deposited with other types of oscillation or without it. Presumably, the effect should be more visible in case of higher feed rates. The application of combinations of oscillations and their parameters may allow to ensure constancy of layers width during the process of obtaining products with a high wall.

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References
[1] Huang Z, Suo H, Gong S, Liu J, Yang G and YangY 2016 Mater. Techn. 31(2) 115-20
[2] Brandl E et al 2011 IOP Conf. Ser.: Mater. Sci. Eng. 26 012004
[3] Tayon W A, Shenoy R N, Redding M R et al. 2014 J. Manuf. Sci. Eng. 136 61005
[4] Waters B R 2018 Mechanical Properties of Inconel 718 Processed Using Electron Beam Free Form Fabrication (EBF3) (Brigham Young University: Master of Science Thesis) p 65
[5] Brice C A and Hofmeister W H 2013 Metal and Mat Trans A 44 5147
[6] Tarasov S Y, Filippov A V, Savchenko N L, Fortuna S V, Rubtsov V E, Kolubaev E A et al. 2018 Int. J. Adv. Manuf. Technol. 99 (9-12) 2353-2363
[7] Tang Q, Pang S, Chen B, Suo H and Zhou J 2014 Int. J. Heat and Mass Transfer 78 203-15
[8] Hu R et. al. 2019 Sci. and Technology of Welding and Joining 24(5) 401-11
[9] Sliva A P 2017 Proc. 2nd Int. Conf. “Electron Beam Welding and Related Technologies” (Moscow: MPEI) pp 506-20
[10] Kim C S 1975 Thermophysical Properties of Stainless Steels (USA: Argonne Nat. Lab.) p 24