Influence of electron beam oscillation parameters on the formation of details by electron beam metal wire deposition method

A V Gudenko and A P Sliva
National Research University “Moscow Power Engineering Institute”, 14, Krasnokazarmennaya str., Moscow, 111250, Russia

e-mail: SlivaAP@mpei.ru

Abstract. The paper is devoted to investigation of electron beam oscillation parameters influence on the geometry of deposited layers of items by means of electron beam metal wire deposition method. The results of sawtooth, zigzag, sinusoidal and elliptical oscillations application in frequency range of 12.5 ... 100 Hz are described. It is established that using of a sawtooth oscillation facilitates liquid metal flow to the weld pool tail and leads to formation of the narrowest and highest deposited layers. Stabilization of all explored deposited layers geometric parameters is occurred at electron beam oscillation with the frequency of 50 Hz and higher. It was also established that the oscillation amplitude rise leads to increasing of deposited layer dimensions due to redistribution of electron beam energy.

1. Introduction
Additive technologies are a promising direction in manufacturing of products from various materials. It is possible to create complex and reliable constructions due to the possibility of layer-by-layer products formation directly from a three-dimensional computer model. Manufacturing of products by this method allows to increase significantly the production efficiency with a reduction of the material expenditure [1].

Nowadays, the dozens of three-dimensional printing technologies are widely used for products fabrication. Electron Beam Metal Wire Deposition Method (Electron Beam Free Form Fabrication (EBFFF), Electron Beam Additive Manufacturing (EBAM)) [2] is one of the most promising methods of fabrication products. The main advantages of this method include high production speed, wide availability of raw materials in the form of metal wire and, as a consequence, a reduction in the cost of finished details [3].

Development of electron beam metal wire deposition technology assumes establishment of connections between main parameters of the process: speed of wire feeding into the treatment zone, deposition rate and energy parameters of electron beam [4]. Correct adjustment of these parameters is a fundamentally important condition for stable flow of metal to substrate and for fabrication of the product with required shape and properties. Now not enough attention has been paid to the influence of electron beam oscillation parameters, which determine distribution of input energy on formation of deposit layers [5]. By changing oscillation parameters together with beam current change, it is possible to achieve the lowest fusion coefficient of base metal and to control the geometry of deposit layers.
Types of oscillations can be divided into two groups. The first group includes circular or elliptic oscillations, as well as oscillations along concentric circles and ellipses. These types of oscillations have an impact on electron beam energy distribution in active zone.

The second group includes oscillations that affect the nature of metal’s flow in a weld pool. The authors of [6] showed that using of certain types of oscillations with a defined frequency makes it possible to influence on metal’s flow in a weld pool. This group includes sawtooth, zigzag and sinusoidal oscillations (figure 1). Using of sinusoidal and zigzag oscillations allows to obtain the advantages of sawtooth sweep, as well as to control width of formed deposited layers. The aim of this work is to study the influence of electron beam oscillations type and parameters on geometric parameters of deposited layer.

2. Research methods
In the experiments on the formation of deposited layer by electron beam metal wire deposition method the wire of 1.2 mm diameter from austenitic corrosion-resistant AISI 316L steel was used. The 5 mm thickness plates of corrosion-resistant austenitic 12Kh18N10T steel were used as a substrate. These plates were mounted on a massive copper substrate and rigidly fixed at the edges. Chemical compositions of steels are shown in table 1.

| Material                              | C  | Mn  | Si  | P   | S   | Cr  | Mo  | Ni  | N   | Ti  | Fe  |
|---------------------------------------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| AISI 316L (wire)                      | 0.03 | 2.0 | 0.75 | 0.045 | 0.03 | 18.0 | 3.0  | 14  | 0.1 | –   | bal.|
| 12Kh18N10T (substrate)                | 0.12 | 2.0 | 0.8  | 0.045 | 0.03 | 18.0 | –    | 10  | 0.8 | –   | bal.|

Influence of the following types of oscillations (figure 1): zigzag, sawtooth, sinusoidal and in the form of concentric ellipses and their parameters on the formation of deposited layers was investigated.

![Figure 1](https://example.com/figure1.png)

Figure 1. Different types of oscillations: zigzag (a), sinusoidal (b), in the form of concentric ellipses (c), x – deposition direction; $A_x$ and $A_y$ – oscillation amplitudes.

The main parameters of electron beam oscillation are frequency $f$ and amplitudes $A_x$ and $A_y$. When using a sawtooth oscillation, electron beam performs a cyclic motion along a straight line in the direction opposite to the deposition direction at a constant speed. This speed is determined by frequency $f$ and amplitude $A_x$. The main beam movement when using sawtooth, zigzag or sinusoidal forms of oscillations...
is directed to crystallization front of weld pool. The main difference between zigzag and sinusoidal oscillations from sawtooth oscillations is that they possess not only the longitudinal amplitude $A_x$, but also the transverse $A_y$. This allows to distribute energy of electron beam both along deposition direction, and across it. Investigation of the influence of oscillation frequency on the geometry of deposited layer was carried out in the frequency range from 12.5 Hz up to 100 Hz. The influence of transverse amplitude $A_y$ on the geometry of deposited layers was investigated for amplitude values in the range from 0 up to 2 mm. Metal wire in the process of layer’s deposition was fed in the direction perpendicular to the direction of depositing (figure 2). All deposited layers were obtained at constant accelerating voltage $U$, wire feed speed $w$, deposition speed $V$ and longitudinal amplitude $A_x$. Constant parameters of the mode are shown in table 2.

![Figure 2. Direction of wire feed [7].](image)

### Table 2. Constant parameters of deposition mode.

| Parameter                               | Symbol | Meaning |
|-----------------------------------------|--------|---------|
| Accelerating voltage                    | $U$ (kV) | 60      |
| Wire feed speed                         | $w$ (mm·s$^{-1}$) | 40      |
| Deposition speed                        | $V$ (mm·min$^{-1}$) | 651     |
| Longitudinal amplitude of oscillation   | $A_x$ (mm) | 2.45    |

After the deposition, cross-sections were made from the samples and were examined with using an optical microscope Zeiss Observer Z1. To assess the efficiency of different oscillation types, geometric parameters of deposited layers’ cross-sections were defined in at least three sections of each layer. These parameters are: layer’s height $H$, layer’s width $B$, height/width ratio $H/B$, area of deposited metal ($F_{n}$), area of substrate’s penetration ($F_{o}$), area of molten metal ($F$) and deposited metal share $\gamma = F_{n}/F$.

### 3. Results of studies

When comparing different geometrical parameters of the cross-sections of deposit layers (figure 3), obtained with different types of oscillations, it was established that when using a sawtooth oscillation, deposited layers are the highest and at the same time have the smallest width. Also they have the largest share of deposited metal (table 3, figures 4 and 5).
Figure 3. Cross-sections of deposited layers made with different types of oscillations: sawtooth (a), zigzag (b), sinusoidal (c), in the form of concentric ellipses (d).

Table 3. Parameters of deposition mode and deposited layers geometric parameters for the deposition with different oscillation types.

| Parameters of deposition mode | Geometric parameters of deposited layers |
|-------------------------------|------------------------------------------|
| $I$ (mA) | $f$ (Hz) | $A_t$ (mm) | Type of oscillation | $H$ (mm) | $B$ (mm) | $H/B$ | $F$ (mm$^2$) | $\gamma$ |
| 31 | 50 | 0.96 | | Sawtooth | 2.00 | 3.16 | 0.63 | 8.92 | 0.54 |
| | | | Zigzag | 1.92 | 3.63 | 0.53 | 9.54 | 0.54 |
| | | | Sinusoidal | 1.86 | 3.39 | 0.48 | 9.75 | 0.48 |
| | | | Concentric ellipses | 1.80 | 3.24 | 0.51 | 8.93 | 0.51 |

Figure 4. Oscillation type impact on the deposited layers geometric parameters.

Using of zigzag oscillation, conversely, leads to the formation of deposited layers with a minimum height and maximum width in comparison with other types of electron beam oscillation. An applying of oscillations in the form of concentric ellipses doesn’t lead to layer’s height growth because electron beam movement doesn’t influence on metal’s flow in weld pool. When oscillations in the form of concentric ellipses are used, energy is concentrated closer to the center of oscillations, while sinusoidal and zigzag oscillations using allows to distribute energy more uniformly across deposited layer. Due to such nature of energy distribution, deposited layers are narrower when oscillations in the form of concentric ellipses are used.
Figure 5. Oscillation type impact on the molten metal area \( (F) \) and deposited metal share \( (\gamma) \).

Using of sawtooth oscillations ensures more effective metal’s flow to the tail of weld pool that allows to get higher and narrower deposited layers. When using such oscillations, beam energy is distributed only along the weld pool, but not across it, which also contributes to obtaining a narrow deposited layer.

For obtaining of deposition metal stable width at the process of multi-pass deposition, it is advisable to combine different types of oscillations, smoothly changing from zigzag or sinusoidal oscillations to sawtooth oscillations and reducing amplitude of oscillations \( A_y \) as the wall height increases.

Changing oscillation frequency when applying zigzag, sinusoidal or sawtooth oscillations affects the intensity of metal’s flow to the tail part of weld pool, similar to its effect on metal’s flow during the process of electron-beam welding (EBW) [6]. Parameters of deposition mode for investigation the effect of oscillation frequency on the formation of deposited layers are presented in table 4; cross-sections of resulting deposited layers are shown in figure 6.

The relationship between geometric parameters of deposited layers and the frequency of zigzag oscillation is shown in figure 7. It shows that increasing in oscillation frequency leads to increasing in the height of deposited layers \( H \) and increasing in the deposited metal share \( \gamma \) (figure 8).

Table 4. Parameters of deposition mode and deposited layers geometric parameters for the deposition with various frequency \( f \).
Figure 6. Cross-sections of deposited layers. Oscillation form is zigzag: \( f = 12.5 \) Hz (a); \( f = 25 \) Hz (b); \( f = 50 \) Hz (c), \( f = 100 \) Hz (d).

Figure 7. Frequency \( f \) impact on deposited layers geometric parameters (zigzag oscillation).

Figure 8. Frequency \( f \) impact on the molten metal area \( F \) and deposited metal share \( \gamma \) (zigzag oscillation).

Starting at a frequency of 25 Hz, change in height, width and their relationship with each other is fairly smooth. Height of deposited layers and deposited metal share reach the highest value at a frequency of 50 Hz. A further increase in frequency does not lead to a sufficient change in these parameters. The narrowest deposited layer is observed at a frequency of 100 Hz. Large height at the
oscillation frequency of 12.5 Hz is probably associated with "scaly" surface of deposited layer due to low oscillation frequency. In this case, a sufficiently deep penetration of substrate is observed; this indicates the excess power of electron beam (beam current is 31 mA). It is necessary to minimize energy introduced by means of an electron beam in the material for such process in order to reduce deformations and avoid overheating of substrate. This is especially important for multilayer deposition, where it is necessary to avoid overheating of substrate and metal’s spreading and, as a result, increasing the width of deposited layers.

Investigation of frequency influence for sinusoidal oscillations was carried out at a beam current of 24 mA. In this case, a significant reduction in the area of molten metal is observed due to decrease in the penetration of substrate (figure 9). Height $H$ and width $B$ of deposited layers are reduced in the frequency range from 25 Hz up to 50 Hz (figures 10 and 11). These parameters stabilize at a frequency of 50 Hz. Deposited metal share, on the contrary, increases with increasing frequency from 25 to 50 Hz and then stabilizes. Further increasing in frequency does not lead to a change in geometry of deposited layers and penetration zone. A stable formation of high and wide deposited layer is observed at a frequency of 12.5 Hz.

![Cross-sections of deposited layers](image1)

**Figure 9.** Cross-sections of deposited layers. Oscillation form is sinusoidal: $f = 12.5$ Hz (a); $f = 25$ Hz (b); $f = 50$ Hz (c), $f = 100$ Hz (d).

![Graph](image2)

**Figure 10.** Frequency $f$ impact on deposited layers geometric parameters (sinusoidal oscillation).
Figure 11. Frequency $f$ impact on the molten metal area $F$ and deposited metal share $\gamma$ (sinusoidal oscillation).

Change of geometric parameters at sinusoidal oscillations and current of 24 mA does not coincide with their changing at a current of 31 mA and zigzag oscillations. Relative magnitudes (deposited metal share and height/width ratio) change in a similar way. The share of deposited metal increased with decreasing current. The deposited layers turned out to be narrower and higher in comparison with the previous case. Such change in geometry is associated with less heating of liquid metal. The lower heat input into the metal, the greater surface stress factor of metal, therefore metal will not spread over the surface of substrate.

It is obvious that change of oscillation amplitude influence on the dimensions of weld pool. By means of controlling oscillation amplitude in transverse direction with respect to deposition direction, it is possible to adjust width of liquid bath and, therefore, width of deposited layer. The effect of change in the oscillation amplitude across the deposition direction on the geometry of deposited layer was studied using a zigzag oscillation at a frequency of 50 Hz. The deposition regimes and parameters of deposited layers are shown in table 5. Cross-sections of layers deposited at different amplitudes $A_y$ are shown in figure 12.

As expected, increasing of the amplitude leads to increasing of deposited layer’s width and decreasing of its height (figure 13), while deposited metal share decreases (figure 14). The widest deposited layer is observed at the largest amplitude. It is possible to influence the width of deposited layer in a small range by adjusting amplitude. A limiting factor of influence on the width of deposited layer is a wire diameter at constant deposition speed and wire feed rate.

Table 5. Transverse oscillation amplitude $A_y$ and parameters of deposition mode impact on deposited layers geometric parameters.

| Parameters of deposition mode | Geometric parameters of deposited layers |
|------------------------------|----------------------------------------|
| $I$ (mA) | $f$ (Hz) | Type of oscillation | $A_y$ (mm) | $H$ (mm) | $B$ (mm) | $H/B$ | $F$ (mm$^2$) | $\gamma$ |
| 31 | 50 | Zigzag | 0 | 2.00 | 3.16 | 0.63 | 8.92 | 0.54 |
| | | | 0.48 | 1.87 | 3.29 | 0.57 | 8.39 | 0.56 |
| | | | 0.96 | 1.92 | 3.63 | 0.53 | 9.54 | 0.54 |
| | | | 1.44 | 1.89 | 3.46 | 0.55 | 8.94 | 0.55 |
| | | | 1.96 | 1.59 | 3.87 | 0.41 | 9.21 | 0.46 |
Figure 12. Cross-sections of deposited layers obtained with different transverse amplitude $A_y$: 0 mm (a), 0.48 mm (b), 0.96 mm (c), 1.44 mm (d), 1.92 mm (e). Oscillation form is zigzag.

Figure 13. Transverse amplitude $A_y$ impact on deposited layers geometric parameters (zigzag oscillation, $f = 50$ Hz).

Figure 14. Transverse amplitude $A_y$ impact on the molten metal area $F$ and deposited metal share $\gamma$ (zigzag oscillation, $f = 50$ Hz).

4. Conclusions
Using of electron beam oscillations leads to redistribution of energy in the treatment zone in such a way as to avoid evaporation and spattering of metal. An applying of sawtooth, zigzag and sinusoidal oscillations makes it possible to influence on the transfer of liquid metal in weld pool.
Using of a sawtooth oscillation makes it possible to redistribute energy without increasing the width of deposited layers and also allows move liquid metal to the tail of weld pool, thereby increasing the height of deposited layer.

Combining sawtooth and zigzag or sinusoidal oscillations with smoothly changing of transverse amplitude $A_y$ is expediently for obtaining stable width of deposited layers’ walls.

Changing oscillation frequency in the case of applying a zigzag, sinusoidal or sawtooth oscillations influence on the intensity of metal’s transfer to the tail part of weld pool and on the stability of deposited layers formation. An increase of layers’ height occurs with increasing of oscillation frequency up to 50 Hz, when the process of deposition is stabilized.

With an increase in the transverse amplitude of oscillations an increase of the width and a decrease of the deposited layer height is observed due to changing of beam energy distribution across deposited layer. It is possible to influence on the width of deposited layer within rather small range by means of oscillations amplitude varying. A limiting factor of influence on the width of deposited layer is a wire diameter at constant deposition speed and wire feed rate.

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