Enhancement of Deposition Process Controlling in Electron Beam Metal Wire Deposition Method

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Abstract. The urgency of improving control systems for electron beam metal wire deposition method is proved in terms of creating methods for controlling the geometric parameters of deposited layer. It is shown that to solve this problem in electron beam metal wire deposition method, it is advisable to use reflected electron signal detection when scanning the deposited layer. Using a mathematical model based on the application of continuous loss approximation and Monte-Carlo method, the probe characteristics recorded during cylindrical layer scanning are investigated. Experimental verification of the results obtained was carried out using an electron-beam technological installation. The effect of the distance between the layer and electron collector on the recorded signals is investigated. The possibility of using this method for simultaneous control of deposited layer height and width is shown.

1. Introduction
The electron beam metal wire deposition technology has been actively developed in the last decade. Technologies have been developed based on the use of a laser beam [1], an electric arc [2] and other types of electric heating, implemented in a protective gas environment. When implementing these technologies, it is extremely important to continuously monitor the deposited layer height. This is necessary for the correct selection of deposition tool lifting speed during the transition from the previous layer to the next. In addition, it is important to know the geometrical dimensions of the layer being formed – its height and width. To solve the set tasks in the implementation of the above technologies, machine vision systems [3] and 2D laser scanners [4] are used. Continuous monitoring of height and width of the layer being deposited allows adjusting the main process parameters – speed of deposition tool movement and wire feed speed, as well as stabilizing distance between the deposition tool and the layer. In the case of electron beam using as a heating source, such difficulties for optical sensors using arise as intense metal evaporation in a vacuum chamber closed volume and overheating of electronic components. An alternative solution that reduces both the cost and the technical complexity of such control system is reflected electron signals using, generated during layer surface scanning. Such solutions have been developed and applied for a long time to detect the joint of parts in electron beam welding [5, 6], and even for automatic joint tracking [7]. The joint is a narrow deep slit, when combined with which most of the reflected electrons are absorbed. Therefore, when a signal is detected, a “contrast” is formed between the joint and the surrounding surfaces of parts. When electron beam
metal wire deposition method using, such a sharp contrast is not observed, and the surface on which the layer is deposited can have a very different shape. Therefore, confirmation of the efficiency of reflected electron detectors application for determining of deposited layer height and width requires additional research.

2. Proposed control method

Figure 1a shows a typical form of a single deposited layer, obtained by electron beam metal wire deposition method [8]. It can be seen that the roll in cross section has a shape close to a semicircle, and the ratio of the roll height to its width is approximately equal to one. Figure 1b shows a diagram of deposited layer scanning process. Electron beam 1 is periodically deflected onto the already formed layer 2 and crosses it at a constant speed in a direction perpendicular to the direction of metal’s deposition. A magnetic deflection coil is used for beam's deflection. During scanning periods, the metal heating process is interrupted, however, this should not affect heat and mass transfer, since time period spent on scanning is small (no more than a few milliseconds). It is important that plasma processes do not affect measured signal during scanning. When interacting with layer surface, flows of backscattered electrons 3 will be created, some of which will fall on the collector 4. The flux intensity and angular distribution of backscattered electrons will depend on the inclination angle of metal surface to the beam [9]. The re-reflection of electrons from layer surface will also play a role. The reflected electrons current flowing through the measuring resistor 5 will be small (usually 0.01-1% of the beam current), therefore, amplifier 6 is needed to amplify the current signal.

![Figure 1. Layers shape deposited in the Electron Beam Free Form Fabrication process (EBF3 process) (a) and diagram of layer surface scanning process with detection of backscattered electron signal (b): 1 – scanning beam, 2 – deposited layer, 3 – backscattered electrons, 4 – collector (or several collectors), 5 – measuring shunt, 6 – signal amplifier.](image)

Figure 1 also shows such geometrical parameters of deposited layer as its width B and height H. The reflected electron detector is installed at a distance L from the deposited layer and is rigidly attached to an electron gun with a wire feeder.

3. Simulation of scanning process and verification

To study the influence of scanning process geometric parameters on the recorded signal, a mathematical model based on the continuous loss approximation was used [9]. The stopping power, or electron energy loss per unit path length, was determined according to the expression
\[ \frac{-dE}{dS} = -2\pi e^4 N \frac{Z \cdot \rho}{A \cdot E} \ln \left( \frac{1.166E}{J} \right). \]  

where \( E \) is electron energy current value, keV, \( S \) is electron path, cm, \( e \) is electron charge, C; other parameters refer to the material: \( Z \) is atomic number, \( \rho \) is density, g/cm\(^3\), \( A \) is atomic mass, g/mol, \( J \) is ionization potential, keV, which is determined by the expression:

\[ J = (9.76Z + 58.5Z^{0.19}) \cdot 10^{-3}. \]

In accordance with the indicated approximation, it is assumed that only elastic scattering acts lead to electrons deflection at significant angles. The elastic scattering cross section was calculated by the expression

\[ \sigma_E = 5.21 \cdot 10^{-21} \frac{Z^2}{E^2} \cdot \frac{4\pi}{\alpha(1+\alpha)} \left( \frac{E + 511}{E + 1024} \right)^2, \]

where \( \alpha \) is screening parameter determined by the Bishop formula

\[ \alpha = 3.4 \cdot 10^{-3} Z^{0.67}. \]

The most probable mean free path is

\[ \lambda_E = \frac{A}{N \cdot \rho \cdot \sigma_E}. \]

The electron beam in the model is represented in the form of a finite number of electrons having equal energies and distributed over a circle in accordance with normal distribution law \([10]\). It is assumed that the electron experiences elastic scattering at some point P1, arriving in it from the point P0. The main task of modeling is to calculate the coordinate of the point P2, where the electron arrives. To calculate this coordinate, it is necessary to determine electron path \( s \), as well as solid scattering angle \( \phi \) and azimuthal scattering angle \( \psi \) \([8, 9]\). In accordance with Monte Carlo method, electron path between elastic scattering events is determined by the expression

\[ s_E = -\lambda_E \cdot \ln \gamma, \]

where \( \gamma \) is a random value selected from the range from 0 to 1. The next step is to calculate the scattering angles. Based on the Rutherford model, we use the Reimer-Krefting expression to determine cosine of elastic scattering angle:

\[ \cos \phi = 1 - \frac{2\alpha \gamma}{1 + \alpha - \gamma}. \]

The azimuth angle is determined randomly:

\[ \psi = 2\pi \gamma. \]

Expression (1) shows that electron energy loss per unit path length will depend on the current value of particle energy, as well as on the material properties. Electron trajectory range between acts of elastic scattering leading to deflection at significant angles (and the angle itself) will also depend on the material properties. Using expressions (1)–(8), a computer program was developed to simulate electron beam (with an energy of 60 keV) scattering process when interacting with a steel layer (calculations were carried out for pure iron) \([11, 13, 16, 17]\). To simulate scanning, beam angle of incidence on the layer \( \theta \) was changing. Layer height and distance between layer surface and collector
were taken as variable parameters. The number of calculated particle trajectories is 10 000. The simulation results are shown in figure 2.

![Image](image.jpg)

**Figure 2.** Dependences of the ratio between collector and beam currents ($I_c/I_b$) on beam deflection angle $\theta$ obtained using the model.

The experimental results presented in figure 3 also show that the probe characteristics can be used to determine the distance between detector and layer surface, as well as layer width. The minimum values of recorded signal can be interpreted as corresponding to beam position near the vertical edges of the layer being formed. The waveforms shown in figure 3 correspond to the case when beam deflection angle is small, and distance between collector and layer is not less than 100 mm. However, in figures 2 and 3, the regions where detector current passes through the minimum are visible, they marked as I. These regions correspond to such time moments at which electron beam crosses layer border, and the reflection of electrons from vertical surface leads to a decrease in the current recorded by the detector [12, 14, 15].

The beam deflection angle in the real case does not exceed 5 degrees, therefore, displacement of the minimum signal regions I with a change in the distance between detector and layer surface is insignificant. However, the signal amplitude changes, and when the layer is positioned close to the detector, it will be maximum. It is advisable to use two detectors to determine the distance between layer surface and electron gun and layer width. The first detector should be narrow (narrower than the layer). It is used to determine the distance between electron gun and layer surface. The second detector can be wider and is used to measure layer width. The recorded current decreased almost to zero due to the fact that the beam was deflected beyond the substrate – to the tooling located below. The described control method is well combined with other proposed methods based on the measurement of probe signals [18, 19, 20].

**Conclusions**

1. A method based on reflected electron signal measurement is proposed to control the distance between electron gun and layer surface. This method is also suitable for measuring layer width.
2. It is shown that by minimizing scanning time, the method is suitable for continuous measurement of deposited layer height and width. This is extremely important for building a control system for the additive forming process.
This control method can be implemented by means of a neural network control system and introduced into the numerical program control system of an electron-beam technological installation.

![Waveform Image](image)

**Figure 3.** Waveforms obtained experimentally when scanning the deposited layer at various values of relative displacement between layer surface and detector (position 0 mm corresponds to a distance of about 100 mm).

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Acknowledgments
This study conducted by Moscow Power Engineering Institute was financially supported by the Ministry of Science and Higher Education of the Russian Federation (project No. FSWF-2020-0023).