ON IMPROVING THE METHOD OF ELECTRON-BEAM DEPOSITION

Konstantin A. Rozhkov1, 2, a, Sergey S. Starikov1, 3, Stepan V. Varushkin1, Dmitry N. Trushnikov1, Irina A. Zubko1

1) Perm National Research Polytechnic University
2) Perm Plant Mashinostroitel, AO
3) Perm Scientific and Production Instrument-Making Company, PAO

a) 614056, Russia, Perm, 57 Novozyaginskaya street, e-mail: k-rozhkov@mail.ru, tel.: +79523277903 614056

Abstract. The paper deals with improvement of the electron-beam additive forming of metal products using a vertically fed filler wire in vacuum with two electron beams as a heating source. We compared the importance of the power of the heat source required for fusing the layers with each other and the calculated power of the heat source required to melt the filler wire and the surface of the product. Within the experimental conditions of the multilayer electron beam deposition using side wire feeding, the electron beam power of 2.4 kW was required to ensure fusion without the defect formation between the layers during the deposition of Ti-6Al-4V titanium alloy. At the same time, approximate calculations of the minimum power of the heat source required to melt the filler wire and the surface of the product showed a level of 730 W.

1. Introduction

Fast depositing production facilities require more productive and low-cost technologies to create complex geometries of workpieces. This trend stimulates development of additive technologies, which require minimal pre-production costs and manufacture workpieces, which cannot be obtained by other methods. Additive manufacturing is a breakthrough innovative technology that can replace traditional methods. This technology is based on creating a physical object from an electronic geometric model by adding materials, as a rule, layer by layer, in contrast to subtractive manufacturing (machining) and traditional shape-forming manufacturing (casting, stamping).

At present, additive technologies are developing in many directions with a great variety of their methods and types, used materials and their conditions, sources of energy for melting and methods of applying materials. The electron-beam additive technology is one of the promising areas of such methods for producing parts. This technology has already gained various commercial names, i.e. Electron Beam Freeform Fabrication (EB-FFF), Electron Beam Additive Manufacturing (EBAM). The additive electron beam deposition for products from titanium alloys is a promising tool aimed at reducing their manufacturing costs. A large amount of papers in this area proves this issue to be relevant.
The use of a wire as a filler material has great advantages over the use of powders including high productivity, high quality of the synthesized material, high utilization of the material from which a part is made [5, 6].

The listed advantages of the electron-beam method make it possible to manufacture large critical products from chemically active metals, which is the main application of this method.

Further, the paper discusses main problems of the wire-fed electron-beam additive forming and their solutions, including a completely new process design.

2. Prerequisites for the development of the electron-beam method with a vertically fed wire

The conventional design of the wire-based electron-beam additive technology consists in using the electron beam on a product’s surface with the side feeding of the filler wire into the electron beam-product zone of interaction [7]. The design diagram is shown in Fig. 1. To provide deposition in a required direction, one can rotate or move a product along a certain trajectory. In this case, the wire is fed at a slight angle to the surface of the product.

![Fig. 1. A standard design scheme of the electron-beam deposition](image)

This design of the additive manufacturing process has several significant disadvantages:

1. Due to the asymmetric wire feed, the heat distribution and hydrodynamic processes in the deposited region, thus, the quality of the deposited regions, depend on the filler wire placement relative to the deposition direction.

   Specialists of the Institute of Physics and Mathematics, SB RAS, studied how different directions of the wire feed affect the manufacturing process. The manufactured sample was deposited by moving the gun with a wire feed mouthpiece on the stationary substrate, so the angle of the wire feed relative to the manufacturing direction was constantly changing. Typical regions and photos of the deposited sample are shown in Fig. 2 [8].

   The results of the published works show how the wire feed angle relative to the motion direction affects the quality of the deposited material. By changing this angle, one gets unsatisfactory formations in some regions (1, 3). According to the published works [9, 10, 11, 12] the wire feed angle is usually 30–45º.

2. There is a shaded region of the surface under the wire, on which the deposition is made.

   Electrons fall only on the upper part of the wire, thereby form a shaded region under the wire. This region of the unmolten metal leads to internal defects in the form of discontinuities. The presence of such a shaded region, which the energy of the electron beam does not reach, leads to the need for an additional increase in the power of the thermal effect.
3. Metal heating in the deposition region.

To ensure high quality fusion of the deposited wire with the substrate, a multiple excess of the input heat energy is required in comparison with the minimum one. Overheating forms an inhomogeneous dendritic structure of the synthesized material, which reduces the stability of its mechanical characteristics. Large residual stresses accumulate, and the formed products obtain significant residual deformations.

Currently, there are several ways to solve these problems. The Chinese company Xi’an Zhirong Metal Printing System Co proposes to use several filler wires for electron-beam deposition [13]. Depending on the deposition direction, one of the four filler wires is fed, having a more desired placement relative to the deposition direction. This method helps to make the quality of the deposited layers less dependent on the location of the filler wire relative to the deposition direction, but does not eliminate an excess heat input to ensure fusion in the regions shaded by the wire. In addition, there is a problem of synchronizing several wire feeders, especially in places where they change their actions.

The best solution is offered by the Ukrainian company NVO Chervona Khvilya (xBeam) [2, 14]. The developed method of electron-beam deposition consists in using a specialized electron-beam gun with a hollow cathode having a central hole, through which the filler wire is fed. In this way, the conical electron beam evenly melts the axially fed wire.

3. A new method of electron-beam additive manufacturing

A team of specialists from Perm National Research Polytechnic University and LLC “Center for Electron-Beam and Laser Technologies” together with scientists from Huazhong University of Science and Technology and with the support of OJSC “NITI Progress” and LLC “Inkor” are improving mechanical properties of products and efficiency of the electron-beam wire additive forming of products. As part of this international project, a technology has been developed to manufacture products using the layered deposition of a vertically fed filler wire melted by two inclined electron beams. The technology design is shown in Fig. 3.
Fig. 3. A design scheme of the electron beam deposition with two inclined electron beams and a vertically fed filler wire

This design of the electron-beam additive manufacturing eliminates the above listed disadvantages. The wire is fed vertically and melted from both sides, which provides no dependence of the quality of the synthesized material on the direction of deposition. In this case, it becomes possible to deposit products with complex configurations, the process of melting and deposition is identical in any direction.

The absence of a shaded region excludes the formation of defects associated with it. The use of two beams guarantees a complete melting of the wire and the required activation of the substrate to form a high quality material.

Reduction of heat input into the depositing part is considered as one of the most important advantages of the developed scheme of electron-beam deposition with axial wire feed over the standard scheme with side feed.

4. Estimations of heat input reductions

We assessed the relevance of the suggested technology by finding its maximum possible impact on reducing the required heat supply. The experiments with multilayer wire electron beam deposition with the side wire feed were carried out. Then we compared the obtained power values of the heat source required for fusing the layers with each other with the calculated power of the heat source required to melt the filler wire and the surface of the product.

The experimental studies used TETA 6E250 electron beam facilities upgraded for wire deposition of metal products, the main characteristics of which are presented in Table 1. A 10 mm thick sheet of titanium alloy Ti-6Al-4V was used as a substrate and a Ti-6Al-4V filler wire with a diameter of 2 mm was also used. The deposition design scheme is shown in Figure 4.

| Parameter                                | Value                |
|------------------------------------------|----------------------|
| Accelerating voltage                    | 60 kV                |
| Electron beam current                   | 100 mA               |
| Beam deviation angle                    | ±7°                  |
| Cathode type                            | Indirect heating     |
| Working vacuum                          | 5x10⁻² Pa            |
| Internal dimensions of the vacuum chamber| 500x500x500 mm       |
| Axis movement X,Y,Z                      | 250, 250, 300 mm     |
| Manipulator lifting capacity             | 50 kg                |
Fig. 4. The scheme of multilayer electron beam deposition by side feeding wire

Two modes of electron beam surfacing were experimentally obtained having different power values of the electron beam, which parameters are presented in Table 2. The first mode revealed internal defects of the deposited material. While the specimen deposited in the second mode had a higher quality. Specimens deposited in these modes had dimensions of 100x100x45 mm. X-ray control of the obtained samples was carried out in accordance with the requirements of GOST 7512-82. The views of the samples and the results of their X-ray control are shown in Figure 5.

Table 2. Technological variables of multilayer electron beam deposition by side feeding wire

| Variable                                | Mode № | 1     | 2     |
|-----------------------------------------|--------|-------|-------|
| Electron beam power $P_e$, W            |        | 2100  | 2400  |
| Deposition velocity $V_d$, mm/s         |        | 15    | 15    |
| Filler wire feed speed $V_w$, mm/s      |        | 22.5  | 22.5  |
| Electron beam focusing mode             |        | Focusing on substrate surface | Focusing on substrate surface |
| Filler wire diameter, $D_w$             |        | 2 mm  | 2 mm  |
| Angle between filler wire axis and substrate surface | | 45°   | 45°   |
| Angle between surfacing direction and wire feed direction | | 90°   | 90°   |
Analysis of the X-ray inspection results showed the presence of chains of discontinuities in the sample according to mode 1 (Figure 5 c). The sample in mode 2 is superior in quality to mode 1 (Figure 5 d). Presumably, the power of the heat source of mode 1 is insufficient, and the power value of the heat source of mode 2 is close to the minimum required value for ensure fusion of layers with each other under experimental conditions.

The calculation of the heat source power required to melt the filler wire and the surface of the product is based on well-known equations: the equations for heat required to heat the body and the equations for the mass of the bulk body. Heat losses due to radiation, thermal conductivity to the substrate, and evaporation losses were not taken into account. The characteristics of the substrate and wire material used in the calculations were averaged over the temperature range and are presented in Table 3.

The amount of heat required to heat a body to temperature $T$:

$$Q = Cm(T - T_0)$$

where $C$ is the specific heat capacity; $m$ is the body weight; $T_0$ is the initial body temperature.

Taking into account the latent heat of fusion $H_f$, equation (1) is as follows:

$$Q = Cm(T - T_0) + H_f m$$
To determine the required power of the heat source, let us calculate the required heat for melting the volume of the supplied wire and the surface layer of the substrate per unit time. The depth of the melted surface layer of the substrate $H$ was taken as 0.5 mm, which was defined as 1/3 of the height of the experimentally obtained bead. The width of the surface layer being melted $W$ was taken as 3 mm, which was defined as the width of the experimentally obtained bead. Then the mass of the supplied wire and the surface layer of the substrate per unit time will be:

$$M = \frac{m}{t} = V_w \frac{\pi D^2_w}{4} \rho + V_d H W \rho$$  \hspace{1cm} (3)

where $D_w$ is diameter of the filler wire; $t$ is the time; $\rho$ is density.

Thus, the required power of the heat source necessary to melt the supplied wire and the surface layer of the substrate will be:

$$P = \frac{Q}{t} = CM(T_{melt} - T_0) + H_f M$$  \hspace{1cm} (4)

Table 3. Characteristics of the substrate and wire material used in the calculations

| Parameter                      | Value for substrate and wire |
|--------------------------------|------------------------------|
| Material grade                 | Titanium alloy Ti-6Al-4V     |
| Melting temperature $T_{melt}$ | 1655                         |
| Latent heat of fusion $H_f$    | 315000                       |
| Specific heat $C$, J/(kg·deg)  | 880                          |
| Density $\rho$, kg/m$^3$       | 4450                         |
| Initial body temperature $T_0$| 20                           |

By using equation (4) we calculated the substrate characteristics and wire material from Table 3, the parameters of the second mode from Table 2 and the required power of the heat source. The calculation results revealed the minimum power of the heat source required to melt the filler wire and the surface of the product, i.e. the level of 730 W.

5. Conclusions
The results of the experimental multilayer wire electron beam deposition showed the need for a relatively high power of the heat source. Under the experimental conditions, to ensure fusion without the formation of defects between the layers during the deposition of titanium alloy Ti-6Al-4V, the electron beam power of 2.4 kW was required. At the same time, approximate calculations of the minimum power of the heat source needed to melt the filler wire and the surface of the product showed a level of 730 W. The heat input under the conditions of the experimental part of this work is 3 times higher than the approximately calculated minimum required heat input. The degree of approaching the heat input to the minimum required value when using the developing technology will be evaluated in further work.

Acknowledgements
The work related to modeling the deposition processes is carried out with the financial support of the Ministry of Science and Higher Education of the Russian Federation (State Assignment No. FSNM-2020-0028) and the Russian Foundation for Basic Research (RFBR Project No. 20-48-59606 r_NOTS_Perms Territory), the equipment and technology developments are carried out with the financial support of the Government of the Perm Kray as part of the Scientific Project No. С-26/508.

Recommendations
[1] Surmeneva MA, Khrapov D, Prosolov K, Kozadayeva M, Koptyug A, Volkova A, et al. The influence of chemical etching on porous structure and mechanical properties of the Ti6AL4V Functionally Graded Porous Scaffolds fabricated by EBM. Mater Chem Phys 2022;275.
[2] Davis AE, Kennedy JR, Strong D, Kovalevsk D, Porter S, Prangnell PB. Tailoring equiaxed $\beta$-grain structures in Ti-6Al-4V coaxial electron beam wire additive manufacturing. Mater 2021;20.
[3] Özerinç S, Kaygusuz B, Kaş M, Motallebzadeh A, Nesli Ş, Duygulu Ö, et al. Micromechanical Characterization of Additively Manufactured Ti-6Al-4V Parts Produced by Electron Beam Melting. JOM 2021;73(10):3021-3033.

[4] Jeffs S, Lancaster R, Davies G, Hole W, Roberts B, Stapleton D, et al. Effect of process parameters and build orientation on microstructure and impact energy of electron beam powder bed fused ti-6al-4v. Mater 2021;14(18).

[5] Soundarapandiyan G, Johnston C, Khan RHU, Leung CLA, Lee PD, Hernández-Nava E, et al. The effects of powder reuse on the mechanical response of electron beam additively manufactured Ti6Al4V parts. Addit Manuf 2021;46.

[6] Enhancement of Deposition Process Controlling in Electron Beam Metal Wire Deposition Method. IOP Conference Series: Materials Science and Engineering; 2020.

[7] Joseph C. Benedyk. Additive Manufacturing of Aluminum Alloys // Light Metal Age, Issue 3, 2018.

[8] Kalashnikov KN, Ruhtsov VE, Savchenko NL, Kalashnikova TA, Osipovich KS, Eliseev AA, et al. The effect of wire feed geometry on electron beam freeform 3D printing of complex-shaped samples from Ti-6Al-4V alloy. Int J Adv Manuf Technol 2019;105(7-8):3147-3156.

[9] Fuchs J, Schneider C, Enzinger N. Wire-based additive manufacturing using an electron beam as heat source. Weld World 2018;62(2):267-275.

[10] Teoriia svarochnykh protsessov: Uchebnik dlia vuzov / A.V. Konovalov, A.S. Kurkin, E.L. Makarov, V.M. Neronvni, B.F. Iakushin; Pod red. V.M. Neronvnogo. – M.: Izd-vo MGTU im. N.E. Bauman, 2007 – 752 s. (In Russian)

[11] Marek St. Węglowski, Sylwester Błacha, Robert Jachym, Jan Dutkiewicz, Łukasz Rogal. Electron beam additive manufacturing with wire // «E+E». Vol. 53. Issue 3–4, 2018. Pp.74–78.

[12] T. Leithäuser, P. Woizeschke. Influence of the Wire Feeding on the Wetting Process during Laser Brazing of Aluminum Alloys with Aluminum-Based Braze Material // J. Manuf. Mater. Process. 2019, 3, 83; doi:10.3390/jmmp3040083

[13] Guangyao G., Ning L., Jun Z. The electron beam fuse of vector wire feed increases material device. Patent CN, no. 106984894, 2017.

[14] Kovalchuk D., Melnyk I., Melnyk V., Tugai B. Method and system for manufacturing of three dimensional objects. Paten US, no. 10695835, 2014.