Influence of the beam oscillation parameters on the porosity of electron beam freeform fabricated titanium alloy SPT-2

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Abstract. The effect of electron beam oscillation on the formation of metal during electron beam freeform fabrication has received practically no attention. Nevertheless, it is a variable technological tool that allows to significantly influence the formation of metal during EBFFF process, including the probability of defects formation. The effect of the focus current, the form, and the frequency of the beam oscillation on the formation of pores in single beads by method of electron beam freeform fabrication of the titanium alloy SPT-2 on the substrate of the alloy VT6 was investigated. The porosity of the obtained beads was studied using x-ray images. It was found that too deep an arrangement of the focal plane relative to the substrate surface leads to excessive pore formation. Reducing the oscillation frequency from 1000 Hz to 100 Hz made it possible to completely get rid of the pores in the metal. The use of a spiral-shaped oscillation made it possible to reduce the probability of pore formation in comparison with an oscillation in the form of concentric circles.

1. Introduction

Titanium and its alloys are a widely used material in the aerospace, shipbuilding, and chemical industries due to their low density, high specific strength, corrosion resistance in many aggressive environments, as well as good weldability [1].

The high cost of titanium alloys forces industry to switch from traditional methods of manufacturing of complex geometry designs to additive technologies. A steep increase in the chemical activity of titanium in relation to atmospheric gases at temperatures above 350 °C makes it necessary to reliably protect not only the molten metal, but also the heated parts of the detail above this temperature during the deposition. Due to this fact the most promising method of additive manufacturing of large-sized products is electron beam freeform fabrication (EBFFF) [2-4]. The EBFFF process takes place in a vacuum with a pressure of the order of $1 \cdot 10^{-3}$ Pa. The residual content of atmospheric gases at this pressure is several orders of magnitude lower in comparison with even the purest argon of the highest grade according to GOST 10157-79 [5].

One of the main problems of weldability of titanium alloys is a porosity, which is usually caused by the ingress of hydrogen into the weld pool with moisture adsorbed on the surface of the wire and the base metal, or the presence of dissolved hydrogen in the base metal [1, 6]. However, careful preparation of the wire and the base metal for the deposition does not always allow you to get rid of porosity. The
authors of [7, 8] have found pores that are different from those caused by an excess of hydrogen in titanium in the EBFFS single-layer Ti-6Al-4V beads. The main difference between the "ordinary" pores and the detected ones are the morphology of the inner surface and their larger size. The authors have concluded that the formation of such pores is associated with a significant difference in the evaporation temperatures and the volatility of individual components in the alloy, in particular, aluminum.

One of the main methods of getting rid of porosity is the choice of the optimal EBFFS mode, which consists in regulating the power of the electron beam as well as the surfacing speed and the wire feed speed during a deposition [9]. However, the porosity of the metal can be reduced by adjusting the parameters of the electron beam oscillation. The effect of the beam oscillation on pore formation has been found in the process of laser welding of aluminum alloys [10, 11]. It has been established that the use of the circular beam oscillation allows to reduce porosity. In addition, an increase in the oscillation frequency from 100 Hz to 200 Hz has allowed to completely get rid of the pores in the weld. The electron beam oscillation is not given enough attention as a technological tool that allows influencing the formation of metal in the EBFFS process. It has been found that the electron beam oscillation allows influencing the hydrodynamic processes in a melt pool and makes it possible to regulate the shape of the deposited layers, as well as, probably, the microstructure of metal [12-14]. It is still unclear exactly how the parameters of the electron beam oscillation affect the porosity of the metal in titanium alloys. The optimal choice of not only beam power, feed rate and deposition speed, but also the shape and parameters of the beam oscillation can help to expand the range of permissible modes for formation of defect-free metal in EBFFS process.

The main purpose of the study is to evaluate the influence of the oscillation parameters on the pore formation in titanium alloys.

2. Research methods

Process of EBFFS of single beads was carried out on the AELTK-344-12 electron beam welding installation (JSC "Scientific Research Technological Institute "Progress") with an accelerating voltage of 60 kV equipped with a feed mechanism for filler wire.

The beads were deposited using a wire made of titanium alloy SPT-2 with a diameter of 1.2 mm on a substrate made of VT6 alloy. The chemical composition of the alloys is indicated in Table 1.

Table 1. The chemical composition of VT6 and SPT-2 alloys according to GOST 19807-91 and GOST 27265-87 respectively (in percent).

|    | Fe  | C   | Si  | V   | N   | Ti   | Al  | Zr  | O   | Oth. |
|----|-----|-----|-----|-----|-----|------|-----|-----|-----|------|
| SPT-2 | <0.15 | <0.05 | <0.1 | 2.5 - 3.5 | <0.04 | 89.36 - 92.7 | 3.5 - 4.5 | 1 - 2 | <0.12 | <0.3 |
| VT6  | <0.6  | <0.1  | <0.1 | 3.5 – 5.3 | <0.05 | 86.45 - 90.9 | 5.3 – 6.8 | <0.3 | <0.2  | <0.3 |

The accelerating voltage $U$, the wire feed rate $w$, and the deposition speed $V$ – were held constant in all deposited beads (Table 2). Electron beam current $I_b$ varied in experiments.

In this work, 2 forms of the electron beam oscillation were studied – in the form of 5 concentric circles and in the form of a spiral consisting of 5 turns. A schematic of the oscillations is shown in Figure 1. Amplitude $A_o$ of this oscillation was 4 mm.

After the deposition, the samples were X-rayed to detect pores. The porosity was estimated by determining the total pore area $\Sigma F$ [mm$^2$] from a 2-D X-ray image. Radiography of the samples was performed using the TNX-450/2555T X-ray tube. The accelerating voltage was 100 kV. According to the image quality indicator №31 (GOST 7512-82) the size of the minimum distinguishable defect was 0.1 mm. Fine-grained RT-5D X-ray film was used. Exposure time was 1 min.
### Table 2. Constant deposition parameters.

| Parameter | Value |
|-----------|-------|
| $U$, kV  | 60    |
| $W$, mm/min | 6000 |
| $V$, mm/min | 500  |

### Figure 1. A Schematic image of the studied forms of beam oscillations. (A) 5 concentric circles, (B) Spiral. The amplitude $A_x = 4$ mm.

#### 2.1. The effect of focusing the electron beam on porosity

Focusing of the electron beam is one of the most important parameters of the EBFFF mode, the influence of which on the bead formation, as in the case of the beam oscillation, has not received enough attention. In lots of studies, the deposition is usually performed with a defocused beam, since this leads to the formation of low wide beads with a smooth surface [15, 16]. Changing the focus of the electron beam makes it possible to adjust the power density in the processing area. It can lead to a change of the width of the beads.

The influence of the focusing current $I_f$ on the pore formation was estimated by deposition the beads using the electron beam oscillation in the form of 5 concentric circles (Figure 1(A)) with a frequency $f = 1000$ Hz. In total, 5 beads were made with a step-by-step change of the focus. Each bead was divided into 3 sections, each of them had a certain $I_f$. Sharp focusing was at $I_f = 805$ mA during video surveillance by the secondary electron sensor. The focus parameters are shown in Table 3.

The deposition process was carried out without special preparation of the wire in order to identify the greatest influence of the focusing current on porosity.

### Table 3. The values of the focusing currents during deposition.

| № bead | $I_b$, mA | $I_f$, mA | Section 1 | Section 2 | Section 3 |
|---------|-----------|-----------|-----------|-----------|-----------|
| 1       | 45        | 800       | 805       | 810       |
| 2       |           | 790       | 780       | 780       |
| 3       |           | 771       | 774       | 777       |
| 4       |           | 768       | 765       | 762       |
| 5       |           | 795       | 788       | 783       |

#### 2.2. Influence of the oscillation frequency on porosity

The oscillation in the form of 5 concentric circles was used for the deposition process (Figure 1(A)). The frequencies for deposition of the beads are indicated in Table 4. The deposition process was carried out without special preparation of the wire in order to identify the greatest influence of the focusing current on porosity.
Table 4. Values of the electron beam oscillation frequency and beam current during surfacing.

| № bead | \( f \), Hz | \( I_b \), mA | \( I_f \), mA |
|--------|-------------|--------------|-------------|
| 6      | 1000        |              |             |
| 7      | 500         | 45           | 795         |
| 8      | 250         |              |             |
| 9      | 100         |              |             |

2.3. The effect of the form of the electron beam oscillation on the porosity

Two forms of the beam oscillations were compared – in the form of five concentric circles and in the form of a spiral (figures 1 (A) and (B), respectively). The direction of the oscillation was also adjusted. It determines the direction of the beam movement along the oscillation path. When converging oscillation is used the electron beam begins its movement at the periphery of the oscillation and ends in the center, and with a diverging one – on the contrary. The parameters of the mode and the oscillations for deposition of each bead are indicated in Table 5. This experiment was carried out using a higher \( I_b = 50 \) mA in order to increase the lifetime and temperature of the melt pool for additional degassing.

In addition, before the deposition, surface of the substrate and the wire were etched in the acid solution of HF:HNO\(_3\):H\(_2\)O with a ratio of 1:1:10 for 30 seconds, followed by rinsing with water. Etching was carried out in order to remove the surface gas-saturated alpha case layer.

Table 5. The form and parameters of the electron beam oscillation.

| № bead | \( I_b \), mA | \( I_f \), mA | Oscillation form | Frequency \( f \), Hz | Direction of oscillation |
|--------|--------------|--------------|-----------------|---------------------|-------------------------|
| 10     | 790          |              | Conc. Circles   |                     | Convergent              |
| 11     | 790          |              | Conc. Circles   |                     | Divergent               |
| 12     | 775          |              | Conc. Circles   |                     | Convergent              |
| 13     | 775          | 50           | Conc. Circles   | 100                 | Divergent               |
| 14     | 790          |              | Spiral          |                     | Convergent              |
| 15     | 790          |              | Spiral          |                     | Divergent               |
| 16     | 775          |              | Spiral          |                     | Convergent              |
| 17     | 775          |              | Spiral          |                     | Divergent               |

3. Results

3.1. The effect of focusing the electron beam on porosity

The change in the focusing current affects both the external formation and the porosity of the formed metal during deposition (Figure 2). At the focus beam currents \( I_f > 780 \) mA the surface of the deposited beads is not smooth, the scaliness of the beads is becoming clearly visible, and other irregularities on their surface are also observed. The deposition process was stable in the range of focusing currents up to \( I_f > 810 \) mA. When \( I_f = 810 \) mA the power density was most strongly concentrated on the wire, which had led to its steep evaporation, as a result of which the stability of the process was disturbed.

The quantitative assessment of porosity can be expressed as the total area of the pores \( \Sigma F \) on each section of the bead detected on the X-ray film. At \( I_f = 805 \) mA and 810 mA he pore count was not performed due to a violation of the stability of the deposition process. Nevertheless, there is a tendency to increase the number of pores with a decrease in the focusing current (Figure 3). The decrease in porosity with an increase in \( I_f \) may be due to an increase in the vapor recoil pressure on the melt pool with a sharper focus because of an increase in the power density in the electron beam treatment zone. In turn, an increase in the recoil force of vapors can lead to more intensive mixing of the liquid metal, contributing to degassing.
Figure 2. The appearance of the beads 1-5 and their X-ray image (Table 3). The bead numbers are shown above.

Figure 3. The obtained experimental dependence of the total pore area $\Sigma F$ on the focusing current $I_f$.

3.2. Influence of the oscillation frequency on porosity
A decrease in the oscillation frequency of the electron beam during the deposition has led to a noticeable change in the shape of the beads (Figure 3). At the lowest oscillation frequency, equal to 100 Hz, the bead is the narrowest, but at the same time its axis turns out to be the most curved. Therefore, it can be said that the shape of the bead at such frequencies largely depends on the position of the end of the wire during the deposition. At a frequency of 1000 Hz such a dependence on the position of the wire has not been observed – the line of fusion of the bead with the substrate is rectilinear. Also, at a frequency of
1000 Hz, the surface of the bead is almost smooth. In addition, the formation of fused areas of the substrate along the edges of the beads is observed in case of the frequencies of 250 and 100 Hz. Probably, at such frequencies, the metal does not spread over the entire width of the melt pool.

Reducing the oscillation frequency to 100 Hz has led to pore-free metal formation (Figure 3). The decrease in porosity can be caused by a decrease in the velocity of the electron beam along the oscillation path with a decrease in frequency, which leads to an intensification of mixing of the liquid metal. On the contrary, at the highest frequency \( f = 1000 \) Hz, the greatest porosity of the metal is observed. Liquid metal, due to its mechanical inertia, does not have time to react to the movement of the beam at the scanning frequency, so the degassing rate significantly decreases. The effect of the oscillation on the porosity is minimized at high frequencies, since the source becomes static with respect to the melt pool. Another possible reason may be that the deflecting system of the electron beam gun may incorrectly deflect the electron beam along a necessary trajectory at high oscillation frequencies, and as a result there is no ordered effect on the melt pool from the electron beam and, consequently, there is no additional degassing.

3.3. The effect of the form of the electron beam oscillation on the porosity

The shape of the oscillation primarily affects the redistribution of the power density in the processing zone, as well as the speed of the electron beam along oscillation trajectory. The formation of beads at the same focusing currents has not significantly depended on the form of the selected oscillation. The direction of the oscillation also has not affected the shape of the beads (Figure 6).

At \( I_f = 790 \) mA, all samples (11, 14 and 15), except for sample № 10 (Table 5), have not contain pores. In sample № 10, small single pores with a diameter of up to 100 microns have been found (Figure 6).

At \( I_f = 775 \) mA, the beads 16 and 17, deposited using a spiral-shaped oscillation, has not contained pores. The bead 12 have contained small pores with a diameter of up to 100 microns, evenly distributed along the entire length of the bead. 13th sample has differed from 12th in oscillation direction during deposition. This has led to a greater porosity in comparison with the bead 12, the maximum pore diameter is 400 microns, and the pores are also evenly distributed along the entire length of the roller (Figure 6).

![Figure 4](image_url)

**Figure 4.** The appearance of the beads 6-9 and their X-ray image (Table 4). The bead numbers are shown above.
Figure 5. The total area of the pores of the beads at different oscillation frequencies.

Careful preparation of the wire and substrate, combined with the choice of a sharper focus \((I_f = 790 \text{ mA})\), has significantly reduced the likelihood of pore formation. The influence of the oscillation form is more obvious at a lower focusing current - \(I_f = 775 \text{ mA}\). The use of the spiral oscillation has made it possible to obtain defect-free beads at such a focusing current, in contrast to the oscillations in the form of concentric circles.

10 11 12 13 14 15 16 17

Figures 6. The appearance of the beads 10-17 and X-ray image of beads 10, 12 and 13 (Table 5). The bead numbers are shown above.

The influence of the oscillation form on the porosity may be related to the nature of the beam movement along the oscillation trajectory. In case of using the concentric circle oscillation the electron beam moves sequentially from the outer circle to the inner one in such a way that the angular velocity of the beam \(\omega_b\) is maintained constant. Then the instantaneous velocity of the beam \(V_b\) at the periphery
of the oscillation is higher than in its central part. And the power density is maximum in the center of the scan. Using the spiral oscillation, the speed of the beam along its trajectory is constant \( V_b = \text{const} \) and, consequently, the power density is distributed evenly over the heating area.

It is probably due to the uneven distribution of the power density and beam velocities along the oscillation direction at concentric circles that the appearance of porosity along the bead axis is associated (Figures 2, 4 and 6).

4. Conclusions
The deposition of single beads made of titanium alloy SPT-2 on a VT6 substrate by the method of electron beam freeform fabrication with different focusing parameters, as well as the form and frequency of the electron beam oscillation with the study of the porosity of the obtained beads has allowed to establish the following conclusions:

1. Increasing the power density by adjusting the position of the focal plane of the electron beam leads to a decrease in porosity in the bead. If the beam focus is excessively deepened, the formation of pores in the titanium alloy SPT-2 is possible. The decrease in porosity may be due to an increase in the intensity of mixing of the metal because of sharper focusing, which leads to an increase in the vapor recoil pressure influencing the melt pool. However, it is possible to raise the focusing current to a certain limit, since using a sufficiently sharp focusing, the stability of the process can be disrupted due to putting excessive power into the wire, leading to its sharp evaporation.

2. Reducing the frequency of the oscillation in the form of concentric circles to 100 Hz has allowed to get rid of the pores in the bead, but the shape of the bead at this frequency begins to largely depend on the vibrations of the end of the wire during fabrication. Decreasing in the porosity depends on the intensity of liquid metal mixing. Low frequencies lead to more significant mixing than the higher because of mechanical inertia of liquid metal that makes it unresponsive to the extremely high electron beam velocities when the high oscillation frequencies are used.

3. The use of the spiral oscillation has made it possible to reduce porosity at a focusing current of 775 mA in comparison with the oscillation in the form of concentric circles. The influence of the oscillation form on the porosity relates to the beam velocities along the oscillation trajectory and also to the energy distribution using different types of oscillations.

4. It is necessary to correctly approach the choice of not only the main parameters – the power of the electron beam, the wire feed and surfacing speeds, but also the shape and parameters of the electron beam oscillation, since this can increase the range of permissible modes for the formation of defect-free metal during the electron beam additive manufacturing of titanium alloys.

Acknowledgements
The reported study was funded by RFBR, project number 20-38-90174

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