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A new 3D printing method based on non-vacuum electron beam technology

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Abstract. Electron beam freeform fabrication (EBF3) is one of the rapid manufacturing methods, which produces metal parts using an electron beam and wire feed unit in a layer additive fashion without need of mold or jigs. The main disadvantage of EBF3 is that the process is carried out in a chamber, which not only takes a lot of time to evacuate but also limits the size of the part being printed. Non-vacuum electron beam (NVEB) welding is widely used in industry field as a reason for its high production volumes. So a NVEB 3D printing device based on a non-vacuum electron beam welding machine from SST is designed. A serial of experiments is carried out to get a deep understand of 3D printing processing procedure using non-vacuum electron beam system and find a suitable process window. Result shows that droplet transfer mode is one of the most important parameters which determines the quality of the deposition.

1. Introduction

Now days, there are several ways for metal additive manufacturing (AM), such as EBF3 (Electron Beam Freeform Fabrication), EBSM (Electron Beam Selective Melting), SLM (Selective Laser Melting), WAAM (Wire and Arc Additive Manufacturing), etc. [1] [2] [3] [4]. There are also some other nicknames for AM, like 3-D printing, solid freeform fabrication or direct digital manufacturing [5] [6] [7]. After more than 20 years development, additive manufacturing can create sophisticated parts directly, without need of molds or jigs [4]. Comparing to other rapid manufacturing methods, EBF3 has a higher deposition rate and better quality [8-9]. It has advantages on energy efficiency, size adaptability, material cost and particular on suitability in 0-g environment. This technology is especially suitable for manufacturing reactive alloys, such as aluminum or titanium.

The mechanism of EBF3 is illustrated in figure 1. In the process, the wire is fed into the baseplate and melted by the electron beam. The electron beam gun and the wire feed or the baseplate can be manipulated by the same way as CAM, which has a predetermined trajectory stored in a computer. Solidification occurs after the electron beam passes. Repeating this progress layer by layer, a near-net shape part will be manufactured at last. It is much simpler than the traditional subtractive machining methods [10].

But the main disadvantage of EBF3 is that the process is carried out in a chamber, which not only takes a lot of time to evacuate but also limits the size of the part being printed [11]. Non-vacuum electron beam welding has been firstly used in automotive industry as a reason for its high production volumes. The electron beam welding at atmospheric pressure is now used in many fields, such as welding laboratories, equipment construction [11].
Researchers in the Institute for Material Science at Leibniz University Hannover construct a 3D printing device using NVEB welder PTR NV-EBW 25-175 TU [13]. But only some basic deposited parts are shown. To get a deep understand of 3D printing processing procedure using non-vacuum electron beam system and find a suitable process window for it, a serial of experiments is carried out at ISF in RWTH-Aachen.

2. Experimental layouts
The experiments were carried out on a non-vacuum electron beam-welding machine from SST: EBONOVA G300 DSS. It was used to do high-speed electron beam welding at atmospheric pressure [14]. This machine has following specifications:

- Maximum beam power – 30kw
- Maximum beam current – 200mA
- Maximum accelerating voltage – 170kv
- Working distance (nozzle to work piece) – 5-25mm
- Building volume – 1060mm x 700mm x 1340mm

2.1. Adaptation of the NVEBW system for additive manufacturing
To transform the welding machine to a 3D printing device, as shown in figure 2, a wire feed unit was installed to feed the material into the molten pool. As shown in figure 3, a collimator is placed behind the motor to make the wire straight enough to be fed into the right position of the molten pool. In the first few pre-experiments without collimator, the wire cannot be melt completely, illustrated in figure 4.

![Figure 1. EBF3 manufacturing system.](image)

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**Figure 1. EBF3 manufacturing system.**

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**Figure 2. System composition of 3d printer based on NVEBW machine.**

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**Figure 3. Wire feed unit.**
Pay attention that 4 brackets was placed between the operation platform and baseplate for protection. As shown in figure 5, sometimes the high power electron beam can penetrate the baseplate as a reason of too much heat input.

More stable clamps should be adopted in the future experiments. The waviness of the part built by EBF3 is big [15-16]. The printing procedure will be disrupted when there is a large deformation of the baseplate. The baseplate need to be fixed very tightly to stand up to the residual stress.

3. Experiment procedure

Process repeatability is one of the most important factors that limit the large-scale application of AM [16]. The main aim of the research is to get a deep understand of 3D printing processing procedure using non-vacuum electron beam system and find a suitable process window for it.

3.1. Pre-experiments

Several pre-experiments were carried out to get basic knowledge of the processing procedure. One of the important advantage of EBF3 is the highest deposition rates, which makes it suitable for making large-scale metal structures [18]. To get a high deposition rate, the accelerating voltage was set to 150kv. The energy loss of electron beam is around 50% due to the collision with atmosphere and inner wall of the nozzle.

According to the cooling capacity, the beam current was set to 30mA. In the pre-experiments, the deposition figure was just the simplest line. The deposition length is 150mm.

First, the deposition was carried on a high translation and feeding speed. The translation speed was 500mm/min. The feeding speed was set to 1m/min on the control box. (Due to the ration in the feeding wheel, the real feeding speed was 1.34m/min. To make the comparison easier, the feeding speed mentioned below all meant the display speed on the control box.) As shown in figure 6, the wire was not melt completely at some places due to the lack of heat input.
On the second pre-experiments, the translation speed was decreased to 400mm/min. The feeding speed was set to 0.8m/min. The deposition result was shown in figure 7. The wire was melt completely onto the baseplate. Further experiments was carried out to get a better understand of the influence of feeding speed as shown below.

3.2. Influence of wire feeding speed
Manufacturing cost can be greatly reduced with a high deposition rate. But the wire is not melt completely when the feeding speed is too high. To optimize the deposition rate of this NVEB machine, several experiments were carried out using different feeding speed.

Table 1. Deposition with different feeding speed.

| No. | 1   | 2   | 3   | 4   | 5   | 6   |
|-----|-----|-----|-----|-----|-----|-----|
| Translation speed(m/min) | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Wire feeding speed(m/min) | 0.70 | 0.75 | 0.80 | 0.85 | 0.90 | 0.95 |

As shown in table 1, the wire feeding speed varied from 0.70m/min to 0.95m/min. The beam current, accelerating voltage, deposition length was the same with the pre-experiments.

3.3. Influence of deposition gap between layers
In the deposition procedure, the wire is fed into the moving molten pool, which forms a line. A layer is formed line by line. The final part is formed layer by layer. The deposition gap between layers is important to the quality of the parts. To get a better understand of the influence of deposition gap on part quality, three 10-layer walls with single line were deposited. The deposition gaps between layers in each group are 0.5mm, 0.6mm, 0.7mm respectively. The translation speed was 400mm/min. The feeding speed was set to 0.9m/min. Other parameters is the same with the pre-experiments.

3.4. Influence of droplet transfer mode
In welding process, droplet transfer mode is very important to the final quality of the seam [19]. The wire is fed into different places of the molten pool with the variation of the wire feed unit position. An experiment was designed to find the suitable transfer modes for 3D printing using NVEB machine.

Droplet transfer mode is mainly decided by the distance between the baseplate and the intersection of the center line of the electron beam and the extension line of the wire. Because a, b and α cannot be changed easily. The distance is changed by adjusting the value of c from 12.5mm to 18mm.

As we can see from figure 8, a, b, c were measured before each experiment as follows, 8mm, 11mm, 62°. From formula (1), h is calculated, which varies from -1.3mm to 4.2mm.

\[ h = c - a - b \times \cot(\alpha) \]  

A camera was fixed on the nozzle by aluminum elements to take pictures of the transfer droplets. This camera can shot a video of 1280*720 with a frame rate of 50fps.
4. Results & discussion

4.1. Influence of wire feeding speed
The result is shown in figure 9. In deposition of the sixth line, the wire feed unit didn’t work properly. So another line was processed with the same parameters.

![Figure 9. Deposition with different feeding speed.](image)

As we can see from line 1~3, the deposition is not consistent due to lack of material. And big droplet forms when too much wire is fed into the molten pool. Within the translation speed of 400mm/min, a wire feeding speed during 0.85~0.9m/min seems suitable.

A sample was made to take Macro-photo in the center cross section of the baseplate. As we can see from figure 10, penetration depth decreases with a higher feeding speed. The baseplate takes less energy when the wire consumes more energy. SEM or 3D imaging techniques will be used to see the microstructural defects, such as process-induced porosity, which lead to poor performance without mastering [20] [21].

![Figure 10. Macro image of samples deposited with different feeding speed.](image)

4.2. Influence of deposition gap between layers.
As shown in figure 11, three 10-layer walls were deposited. There is also no obvious difference when deposited single layer within different deposition gap between layers.

A sample was made to take Macro-photo in the center cross section of the baseplate. The microstructures of different layers are different, as shown in figure 12. There is grain refinement in the bottom of the deposition due to heat treatment when depositing the top.

To get more understand on the moving strategy, further experiment focused on influence of different gap between both lines and layers should be done in the future.

![Figure 11. Deposition within different gap between layers.](image)  ![Figure 12. Macro images of samples deposited with different gap between layers.](image)
4.3. Influence of droplet transfer mode
As we can see from figure 13, deposition quality varied obviously within different deposition distance. In line 1~5, big droplets formed when there is a long distance between the baseplate and the point where the wire is melt. Droplets fell into the molten pool mostly by gravity. In line 6~9, the wire was continuously melted in the center of molten pool within a shorter distance between the baseplate and the point where the wire is melted. Within the distance decreased more, the wire is melted at the edge of the molten pool, as shown in line 10~12. The wire bend when touching the baseplate, which makes the process unstable. The penetration depth decreases just a little due to a longer distance between the baseplate and the nozzle.

Transfer modes in other experiments is shown in table 2. A distance during 0.2~1.7mm is much more suitable for deposition using an NVEB machine, which make the droplet transfer time decrease to 0 as we can see from figure 14.

Table 2. Transfer modes within different distance.

| h = 4.2mm | h = 3.7mm | h = 3.2mm | h = 2.7mm |
|-----------|-----------|-----------|-----------|
| h = 2.2mm | h = 1.7mm | h = 1.2mm | h = 0.7mm |
| h = 0.2mm | h = -0.3mm| h = -0.8mm| h = -1.3mm|
5. Summary and conclusion
In this project, a NVEB 3D printing device based on a non-vacuum electron beam welding machine from SST is designed. A serial of experiments are carried out to get a deep understand of 3D printing processing procedure using non-vacuum electron beam system and find a suitable process window. The translation speed need to be set under 400mm/min to form a constant molten pool due to the maximum heat input mentioned above. Some typical figures has been deposited successfully. A number of controlled experiments were designed.

Here are some conclusion,

- The suitable wire feeding speed is around 0.85~0.9m/min. The deposition is not consistent due to lack of material with a low feeding speed. Big droplet forms when too much wire is fed into the molten pool.
- A distance (h: the distance between the baseplate and the point where the wire is melt) during 0.2~1.7mm is much more suitable for deposition using an NVEB machine. Big droplets formed when there is a long distance between the baseplate and the point where the wire is melt. The wire is melted at the edge of the molten pool within a short distance, which make the processing unstable.
- There is also no obvious difference when deposited single layer within different deposition gap between lines or layers.

To get more understand on the moving strategy, further experiment focused on influence of different gap between both lines and layers should be done in the future. A powerful baseplate cooling device need to be designed to get a higher deposition rate instead of waiting several minutes between each lines and layers. The wire feed unit need to be synchronized with the electron beam generator. Then more complicated figures can be test to find the potential of this NVEB 3D printing device.

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