Current Status of Electron Beam Selective Melting Additive Manufacturing Technology

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Abstract. Electron beam selective melting is a metal additive manufacturing technology, through electron beam scanning, melting powder materials, layer-by-layer deposition to manufacture three-dimensional metal parts, suitable for the forming and manufacturing of refractory, high-performance metal materials such as titanium alloys and titanium-aluminum-based alloys. Because it can form high-performance metal parts with complex shapes, it has broad application prospects in aerospace, biomedical, automobile manufacturing and other fields. This article summarizes the principles, compares the advantages of selective melting with laser, shows the modern application of the technology, and points out the current technical difficulties and future development direction.

1. Introduction
Additive manufacturing technology, also known as 3D printing, emerged in the 1980s. This technology uses the discrete-stacking principle to realize the high-precision and rapid manufacturing of complex structures. Compared with equivalent material manufacturing and subtractive manufacturing, the advantages of additive manufacturing are: high-complexity structures can be manufactured, raw materials can be saved, short forming cycles, simple manufacturing processes, and one-time forming. Therefore, it is widely used in aerospace, biomedicine, industrial manufacturing, and personalized customization fields [1].

Due to the high difficulty and wide application of metal additive manufacturing technology, it is the current research hotspot in this field. Up to now, metal additive manufacturing can be divided into cladding deposition and powder bed melting from the feeding method. It can be divided into three types from the energy source: laser, electric arc, and electron beam. Among them, the electron beam selective melting technology is formed under a vacuum environment and preheating conditions, which has the advantages of anti-oxidation and strengthening the internal mechanical properties of the metal. Three kinds of this article mainly summarize the electron beam selective melting technology, including its basic principles, technical advantages, application status, current shortcomings, and future improvements and developments [2].

2. Fundamental
The working components of EBSM are shown in the figure (Figure 1). Because the electron beam is used for irradiated melting. It needs to be provided in a vacuum environment to reduce the electron beam dispersion and deviation caused by the collision of electrons and air molecules, affecting overall product accuracy.
At first, a powder layer is preset on the forming platform. The electron beam scans a section of the three-dimensional model on the powder layer to selectively melt the powder material. By moving the forming platform down and re-laying the metal powder, a new powder layer is obtained. Repeat the process and combine the sections with each other until all the sections of the three-dimensional model are melted. Then, combine them with each other to form a three-dimensional solid part [2].

Regarding the control of the electron beam, a magnetic field deflection coil is usually used to control the drop point of the electron beam to achieve rapid scanning, achieve high temperature with a balanced temperature change, and reduce thermal stress and subsequent heat treatment.

3. Technical advantages
Due to the similarity of the basic principles, electron beam selective melting is often compared with laser selective melting. The advantages of EBSM are listed below [1]:

(1) High power. The electron beam can easily output several kilowatts of power; the output power of most lasers is between 200 and 400 W. The maximum power of electron beam processing can reach several times that of the laser.

(2) High energy utilization rate. The energy utilization rate of the laser is about 15%, and the energy utilization rate of the electron beam can reach more than 90%.

(3) No reflection. Many metal materials have high reflectivity to laser light and have high latent heat of melting, so they are not easy to melt. Once the molten pool is formed, the temperature of the molten pool rises sharply due to the significant decrease in reflectivity, causing the material to vaporize. The electron beam is not affected by the reflection of the material and can be used to manufacture laser-hardened materials.

(4) Easy to focus. During laser focusing, because the lens's focal length is a fixed value, focusing can only be achieved by moving the worktable. At the same time, the electron beam is focused by the current of the condenser lens, so it can achieve focusing at any position.

(5) Fast forming speed. The electron beam can perform two-dimensional scanning, and the scanning frequency can reach 20 kHz. The electron beam has no mechanical inertia, and the beam current is easy to control compared with lasers. It can realize rapid scanning and fast forming speed.

(6) The vacuum is pollution-free. The vacuum environment of the cavity of the electron beam device can prevent the metal powder from oxidizing during the liquid phase sintering process and improve the forming of the material.
4. Application status

4.1. Industrial manufacturing

Application:
(1). CalRAM uses Ti6Al4V to manufacture rocket engine impellers for the U.S. Navy's unmanned air combat system project through the EBSM process. The impellers have complex flow channels. (Figure 2)[2]

(2). The load-bearing body of the steam turbine compressor made by Chernyshev in Moscow using EBSM technology (Figure 3)[2]

(3). Fuel nozzles for the GE LEAP aero engine (Figure 4)[4] is a prominent example with a planned production volume of 25,000 parts. The manufactured part is said to be 25% lighter and stronger than the previous conventional design [4].

4.2. Biomedicine

Advantage: Titanium and titanium alloys have the advantages of low elastic modulus, high specific strength, corrosion resistance, and good biocompatibility [2]. Finished in a vacuum environment, it is more conducive to obtaining products with excellent performance.

Problem: The mismatch between the rigidity of the titanium alloy implant and the human bone will cause stress shielding, resulting in bone resorption and loosening of the prosthesis. Studies have shown that the use of porous structures can effectively reduce the elastic modulus of titanium alloy implants and prevent stress shielding.

Application:
(1). Heinl et al. [6] used electron beam selective melting forming technology to form different types of Ti-6Al-4V grid structures. They found that the elastic modulus of porous titanium formed by SEBM technology and the elastic modulus of human bone Changes within a similar range. This study shows that porous titanium formed by SEBM can be used as a biomedical material for bone replacement.

(2). Heinl et al. [6] used SEBM technology to make a prototype of the Ti-6Al-4V intervertebral fusion cage.

(3). Murr et al. [8] used SEBM technology to manufacture Co–29Cr–6Mo femoral prosthesis with a perforated structure for total knee replacement surgery.

(4). Yan et al. [9] used SEBM technology to manufacture a Ti-6Al-4V scaffold for mandibular reconstruction. (figure 5) [7]
5. Technical difficulties

5.1. “Smoking”
Definition: Powder collapse refers to the phenomenon that metal powder is subjected to a certain external force and flies out around the beam spot, deviating from the original stacking position, resulting in subsequent failure to form [10] (figure 6)[2]. The effect of this phenomenon is that the device cannot continue to be molded, and the density decreases. Today, the reasons for this phenomenon are still being discussed, and the main reasons are as follows.

(1) Part of the kinetic energy of the electrons is converted into the kinetic energy of the powder in the collision, causing it to be displaced. We know that electrons have a certain mass. The electrons will be accelerated to a certain speed to carry more energy to bombard the molten metal powder to provide higher power. The electrons will slow down during the bombardment process, and their kinetic energy is mainly converted into internal energy. Still, part of it is converted into the kinetic energy of the powder in the collision with the powder.

(2) Coulomb force displaces the powder (Sigl et al. systematically analyzed and discussed the causes of powder collapse) [11]. During the bombardment, the metal will gradually carry more negative charges, so when the electron beam approaches the powder surface, it will experience two repulsive Coulomb forces, one from other electrons in the electron beam and the other from the negatively charged metal.

(3) The influence of Lorentz's force. As mentioned earlier, metals will gradually carry more negative charges, so a magnetic field will be directed towards the surface being bombarded. At first, there will be no Lorentz force because the electrons move in parallel to the direction of the magnetic field. But on the metal surface, some electrons will gain horizontal speed after the electrons undergo collision and Coulomb force. At this time, these electrons will obtain the Lorentz force perpendicular to the velocity direction, resulting in the formation of a spiral trajectory.
In view of these phenomena, there are the following solutions.

1. Preheating
   Preheating makes the powder partly melt, forming a sintering neck between the powder particles. The powder particles agglomerate into agglomerates, which strengthens the electrical conductivity of the entire powder layer and reduces the electrostatic repulsion between the powder particles. At the same time, the formation of the sintering neck makes the powder bound and the binding force between the particles is enhanced. This can withstand the impact of the electron beam with a larger current and a higher scanning speed, which is beneficial to prevent the phenomenon of powder collapse [7].

2. Use non-spherical powder
   Compared with spherical powders, the frictional resistance between non-spherical powders is larger, preventing powder collapse to a certain extent. Still, the use of non-spherical powders is likely to cause the scanning line to be broken, discontinuous, and spheroidization [2]. Therefore, a mixed powder of spherical powder and non-spherical powder can be considered.

3. Reasonable scanning path
   Reasonable scanning path planning can also achieve the purpose of controlling warpage and cracking. The electron beam can jump quickly under the drive of a magnetic field to realize multi-point melting. Compared with single-point melting, the temperature field uniformity of multi-point melting is better, and the stress level is lower [2].

Guo Chao et al. found that excessive local energy input can cause surface deformation of the formed part. To avoid surface deformation, the electron beam power should be appropriately reduced in the area where the scan line is short. Avoid whenever possible. If required, they should be used only for brief notes that do not fit conveniently into the text.

5.2. Spheroidization
   Definition: The spheroidization phenomenon is when a large number of isolated metal spheres are formed when the molten metal fails to spread evenly. [12] (Figure 7) [12]
Principle: With the help of Plateau-Rayleigh capillary instability theory, Gusarov et al. [13] pointed out that the spheroidization phenomenon is closely related to the geometry of the molten pool. On a two-dimensional level, the ratio of the length to the width of the molten pool is more than 2.1. Spheroidization phenomenon. Zah et al. [14] verified the rationality of the above theoretical explanation by simulating the morphology of the molten pool with different process parameters of SEBM and observing the spheroidization phenomenon. However, the research results of Korner et al. [15] show that molten metal balls are not formed by splitting long fuse lines. The occurrence of spheroidization is affected by multiple factors such as powder bed density capillary force, and wettability.

Solution: Liu Haitao et al. [16] found that increasing the linear energy density to a certain extent can reduce the occurrence of spheroidization. The study of Cormier et al. [17] found that using preheating to increase the viscosity of the powder and heating the powder to be melted to a certain temperature can effectively reduce the spheroidization.

5.3. Deformed or cracked
Reasons: 1. The large temperature difference and large thermal stress 2. Unreasonable path 3. Excessive energy [2] eventually forms a wavy surface morphology. To avoid surface deformation, the electron beam power should be appropriately reduced in the area where the scan line is short. (Figure 8) [18, 19]

Solution: 1. The temperature field uniformity of multi-point melting is better [2]
2. Appropriately reduce the electron beam power in the area where the scan line is short.
3. Based on the final preheating, the conformal heat treatment process is used. Each layer is melted and scanned to form, and the cold temperature is quickly scanned to prevent stress accumulation through plasticity and creep stress, to reduce deformation and inhibit cracking the goal of. [5, 20]
5.4. Pore
Reason:
1. Since SEBM technology generally uses inert gas atomized spherical powder as raw material, a certain amount of hollow powder is inevitably formed during the gas atomization process. Because the SEBM technology has a faster melting and solidification speed, the gas contained in the hollow powder there is no time to escape so that pores remain in the formed part. The morphology of such pores is mostly regular spherical or quasi-spherical. As shown in Figure 2, the distribution inside the molded part is random, but most of them are distributed inside the crystal grains. Such pores are also difficult to treat after hot isostatic pressing, eliminate. (figure 9)[12]

2. The results of Zaeh et al. [21] showed that when a higher energy density is used, the poor thermal conductivity of the powder can easily cause excessive local heat and the formation of pores without causing spheroidization. There are no effective means.

6. Conclusion
Today, electron beam additive manufacturing has demonstrated its advantages in many fields, such as aerospace, biomedicine, and personalized customization. But as far as current technology is concerned, there is still a lot of room for development.

In terms of materials, electron beam additive manufacturing can develop in the direction of composite materials and functionally graded materials to meet the needs of more complex products.

The customized manufacturing of small batches, low cost, and personalized implants should be considered in terms of finished products. In the production of larger-sized parts, it may be necessary to develop multi-gun coupling to reduce the deflection of the electron beam and decrease focus and accuracy.

For online inspection, multi-scale and multi-physics manufacturing process models require more cross-professional talents. Understanding the physical mechanism of various phenomena and the influence of various factors in the forming process will be more in-depth, and the material performance will be maximized to give full play to the potential of additive manufacturing technology.

In addition, the combination of EBSM technology and numerical control processing technology can realize the combination of adding and reducing materials on the same machine tool, giving full play to their respective advantages and not being limited to one manufacturing method, which will also have broad application prospects.
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