Research on image monitoring method of electron beam selection melting

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Abstract. In order to overcome the problem that the lack of real-time detection technology and the existing detection methods cannot select the process area flexibly in the process of electron beam selective melting, this paper presents a digital electronic imaging method which can monitor the roughness and tiny flaws on the surface of components layer by layer. The digital electronic images were produced by detecting both secondary electrons (SE) and backscattered electrons (BSE) originating from interactions between the electron beam and the metal powder. The imaging principle and the hardware circuit of the system are introduced in detail. Finally, the effectiveness of this design is verified by the experiments.

1. Introduction

Electron beam selective melting (EBSM) is also known as 3D Printing that makes use of an accelerated electron beam to melt metallic powder on a layer-by-layer basis, manufacturing components based on computer-aided design (CAD) models. Compared with traditional casting technology and cutting technology, EBSM is a "bottom-up" method to generate components. It has the advantages of high energy utilization rate, high power density, wide range of processing materials and no pollution in vacuum environment. EBSM can manufacture components that cannot or are difficult to be realized with conventional methods. The mechanical properties and compressive strength of the components are superior to those manufactured by traditional technology. What’s more, EBSM has a broad application prospect in aerospace, biological medicine, cultural creativity fields. After Larson applied for the patent of directly preparing metal parts with powder bed precast melting technology in 1994, EBSM has been widely studied by many countries for its unique advantages. However, EBSM is a process of multiple physical fields coupling and there are various decisive factors, such as the shape of the melting pool, the shape of the beam spot and the size of the beam, the temperature of the melting pool and the uniformity of the powder, which can affect the final quality of the component. At present, several of techniques, such as CCD camera, X-ray and ultrasonic, have been applied to monitor the quality of the EBSM process. The detection techniques all need to add additional devices, which cannot be well coupled with the EBSM equipment, increasing the cost and complexity of the equipment. What’s more, for a CCD camera, the high temperature in the processing area makes it impossible to take photos closely which affects the image clarity. It is troublesome to use the CCD camera because the camera is easy to be contaminated by evaporation of processed materials. So, the CCD camera needs to be cleaned or replaced frequently. Besides, the detection methods are only able to detect the entire or a fixed range of
processing area and cannot select the detection range flexibly. Moreover, it is impossible to zoom-in and focus on the specific regions of processing area to obtain images after the monitoring equipment fixed [1].

In order to overcome these shortcomings, this paper presents a real-time detection technology which can monitor the roughness and tiny flaws on the surface of the components layer-by-layer. This technology could provide information for optimizing the forming process of components and guarantee the quality of components.

2. Forming principle and technological improvement of EBSM
As shown in figure 1, vacuum chamber, anode, focusing coil, deflection coil and forming chamber are the major components of EBSM. The electron beam used for forming component is produced from the tungsten filament cathode and accelerated by a high voltage electrode. Two coils organize and direct the fast moving electron beam. The first one acts as a magnetic lens, which focuses the electron beam to the desired diameter. The second one deflects the focused beam to the target point on the powder bed. When the high-speed electrons strike the metal powder, the kinetic energy is immediately converted into thermal energy [2]. The component is built layer-by-layer and each layer is generated in four steps, see in Figure 2. In the first step, a thin powder layer is applied with stainless steel rake on the build area. During the heating process, the powder is repeatedly heated by scanning the electron beam with a small current. In the third step, the electron beam scans the powder particles where solid material is to form. Finally, the machining platform drops a certain height and repeats the above steps until the component is finished [3].

In EBSM, the quality of each layer not only has an essential impact on the forming of the next layer, but also affects the overall performance of the component. Therefore, after the completion of step 3, the image of the processing layer is obtained by the raster-scanning patter. If the defect of the layer is serious, the process is abandoned directly which can save raw materials. Otherwise, continue processing the next layer. This monitoring method can not only obtain the interior structural information of components but also ensure the quality of components.

3. Principle of secondary electron imaging
The imaging principle EBSM is similar to scanning electron microscope (SEM). When the deflection coil of EBSM controls electron beam to scan the surface of processing area, the high-energy electron beam will interact with the surface of the processing layer and generate different electronic signals, including secondary electrons, backscattered electrons, characteristic X-ray, auger electrons and absorption electrons [4]. SE are generated at a depth of 5-10 nm on the surface of the sample and the SE yield is influenced by the surface morphology of the sample. BSE are produced by collisions between electron beams and atoms. The yield of BSE is usually related to the composition of the sample. In general, under a certain condition of electron beam incidence (acceleration voltage, electron beam current and beam spot size), the formula for the yield of secondary electrons [5] is

$$\delta = \delta_0 \times \sec \theta$$

(1)
Where, \( \delta_0 \) is the secondary electron yield of the sample surface irradiated vertically by the electron beam; \( \theta \) is the normal angle between the electron beam and the sample surface.

The direction of the incident electron beam can be regarded as fixed when the electron beam is scanning the processing area. Because of the uneven surface of the processing area, the electron beam incident to different positions will generate SE with different yield, see in figure 3.

**Figure 3. Schematic diagram of secondary electron system**

4. **Design of secondary electron/backscatter electron detector**

In EBSM, the deflection angle of the electron beam is small. It is believed that the electron beam always irradiates the surface of components vertically and the electron yield is only related to the surface morphology and composition of the sample. The electron beam produces secondary and backscattered electrons during surface scanning. Figure 4 shows a model diagram of the electron detector. Since the SE and BSE are captured by the electron sensor at the same time, the image of surface topography or composition of the component cannot be effectively reflected. So, it is necessary to design a special signal separation system to separate the two signals.

The separation principle [6-7] of SE and BSE is shown in the figure 5. The sample in figure 5 (a) is composed of three materials with different composition and neat surface. The waveform of the two absorption plates is only related to the material of the sample and has nothing to do with the surface morphology of the sample. So, the signals captured by the two absorption plates are the same. \( A_1 + B_1 \): the component information is enhanced. \( A_1 - B_1 \): the composition and morphology information to become a straight line; The sample in figure 5(b) is composed of a single material with undulating surface morphology. When the electron beam scans to the left hypotenuse of the first groove, the SE and BSE are mostly captured by B electron detector. When the other hypotenuse is scanned, the electron collection of the electron detector is exactly the opposite of the above results. \( A_2 + B_2 \): the waveform of the two electron detectors is formed into a straight line, and the surface topography information of the sample is weakened. \( A_2 - B_2 \): the composition information is reduced and the surface topography information is strengthened; The sample in figure 5 (c) is composed of three kinds of materials with undulating surface morphology. The waveform change of two absorbing plates is related to both the sample morphology and the sample composition. \( A_3 + B_3 \): the morphological information becomes a straight line and the component information is strengthened. \( A_3 - B_3 \): the composition information is weakened and the morphology information is strengthened. In summary, the composition and surface morphology information can be separated by two absorbing plates. We can get the 16-bit digital signal after the electronic signal is processed by IV transformation, signal processing and analog-digital conversion. Images of the sample morphology can be obtained from these digital signals.
5. **General designation**

EBSM control system is composed of three parts: core control circuit, scanning control circuit and image acquisition circuit, see in figure 6. In this paper, TMS320C6455 which is produced by American TI company is adopted as the core chip of the whole system. It has abundant peripheral interfaces and high-speed data transmission capacity and it can well meet the performance requirements of the control system. As the core chip, TMS320C6455 is responsible for communication with the host computer and controls the scanning circuit and image acquisition circuit. As shown in figure 3, the host compute sends instructions to TMS0C6455 through the EMAC network. After the core chip receives the instructions, the processor sends a control signal to the bus through the EMIF interface. And then the signal is decoding by CPLD chip which is on each circuit system. When the electron beam scans the surface of the current layer, secondary electrons (SE) and backscattered electrons (BSE) are generated, which can be used for imaging after being transformed into voltage signal.
Figure 7. (a) Typical raster-scanning signals in a two dimension Cartesian plane. (b) The result of raster-scanning pattern.

Figure 8. (a) Hardware design of the detector.

Figure 8. (b) Detector of SE/BSE circuit prototype
6. Scan control system
When a layer of powder is completed, the host computer sends instructions to control the X and Y deflection coil for raster-scanning. The host computer controls 16-bit DAC to output the voltage. Figure 7(a) gives an example of the typical X and Y scan signals during raster-scanning. Figure 7(b) shows the corresponding result of raster-scanning pattern [8]. When a specific area needs to be scanned, we can change the code value of the X/Y DA to output corresponding voltage. In addition, the existing scanning area can be enlarged or narrowed by changing the input value of MDA. This method can not only realize the arbitrary selection of detection area but also alter the magnification of the obtained image without losing the imaging resolution.

7. Hardware circuit design of SE/BSE detector
The signal collected by the electron detector is weak and full of noise. It must go through the signal processing circuit before AD transformation. As shown in figure 8(a) and figure 8(b), the current signal from the electron detector is converted into a voltage signal by the IV converter circuit and the appropriate magnification is selected to get a clear image. The main function of the zeroing circuit is to adjust the zero drift of the amplifying circuit and different modes (addition or subtraction) can be selected in the signal processing circuit to output different signals.

8. Experiment and result analysis
One input of this system is the sinusoidal current signal with 1kHZ frequency and 1mA amplitude, the other one is 0 which all is generated by a signal generator. The collected data of the system is displayed by CCS software real-time, see in figure 9. The input current signal is converted to voltage (-1.3V to +1.3V) by SE/BSE detector circuit. And through AD conversion, the voltage signal is transformed into 16-bit digital signal (0-65536). From the 16-digital signal, we can get the gray value of 0-255 as imaging signal. Accuracy of the analog-to-digital is

\[
\frac{2.6V}{65535} = 0.000039V
\]  

(2)

Figure 9. The result of data acquisition.

As shown in figure 10, the typical change of monitoring area is realized by software programming and the result is displayed by an oscilloscope. DSP controls the deflection of electron beam by a 16-bit DAC. The deflection range of the electron beam is 250mm if the DAC is fully calibrated. So, the minimum step of electron beam deflection is
\[
\frac{250000}{65535} = 3.8\text{um}
\]  
(3)

The scanning range can be enlarged or narrowed by changing the output value of MDA (LTC1597). For example, the deflection range of the electron beam is 25mm if output value of MDA is 0.1. The minimum step of electron beam deflection is 
\[
\frac{25000}{65535} = 0.38\text{um}
\]  
(4)

The minimum deflection step is reduced, which is benefit for keeping the resolution of the image.

![Figure 10. The typical change of monitoring area.](image)

9. Conclusion

The paper presented a digital electronic imaging method which can be used for monitoring the quality of components. This method could realize the arbitrary selection of monitoring area and obtain high resolution images. To summary, the method can overcome the limitations of traditional monitoring methods.

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