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Signal acquisition and scale calibration for beam power density distribution of electron beam welding

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Abstract. The power density distribution of electron beam welding (EBW) is a key factor to reflect the beam quality. The beam quality test system was designed for the actual beam power density distribution of high-voltage EBW. After the analysis of characteristics and phase relationship between the deflection control signal and the acquisition signal, the Post-Trigger mode was proposed for the signal acquisition meanwhile the same external clock source was shared by the control signal and the sampling clock. The power density distribution of beam cross-section was reconstructed using one-dimensional signal that was processed by median filtering, twice signal segmentation and spatial scale calibration. The diameter of beam cross-section was defined by amplitude method and integral method respectively. The measured diameter of integral definition is bigger than that of amplitude definition, but for the ideal distribution the former is smaller than the latter. The measured distribution without symmetrical shape is not concentrated compared to Gaussian distribution.

1. Introduction

Electron beam welding (EBW) is a high power density welding method that has many advantages over conventional techniques. The main advantages of this technique are large depth-to-width ratio, narrow heat-affected zones (HAZ), insignificant deformation and pure chemical composition of weld seam in a vacuum [1].

The process of EBW is influenced by a huge number of process parameters. The actual manufacture and design theory of an EBW electronic gun differ in equipment characteristics. The stability of an electron gun power supply system and vacuum changes could affect the electron beam diameter and power density distribution. The geometry and quality of the weld seam is strongly influenced by the process parameters such as accelerating voltage, beam current, welding speed and focus current. Therefore it is necessary to study the characteristics of the electron beam precisely and measure the electron beam quantity quantitatively, such as focus position, beam diameter and power density distribution [2, 3]. As the extremely high power density is about $10^7$ W/cm$^2$ at the focus spot, it can melt any refractory material, which makes measurement very difficult. S. Rouquette built a
Gaussian source model in EBW and estimated the parameters of the energy dissipation in gas phase zone and liquid phase zone by Levenberg–Marquardt method [4]. Luo study the power density distribution of vacuum EBW under different welding conditions using the finite element model of rotary Gaussian body heat source [5]. The studies mentioned above are based on the ideal model.

In order to get the actual beam power density distribution for high-voltage EBW machine, we had developed the electron beam quality test system. With high-speed magnetic deflection technology, the system controlled the electron beam scanning on the Faraday cup sensor quickly, which solved the problem about high beam power density. As the electron beam welding environments with high electromagnetic interference, the collected signal is mixed with noise. In this paper, firstly the signal is processed by digital filter, and then the time-domain signal is calibrated corresponding to spatial scale, finally the power density distribution and beam spot diameter of electron beam cross-section is calculated by the special software.

2. Principle and Structure of the System
Fig. 1 represents a schematic diagram of the beam quality test system used for the electron beam measurements before welding process. Driven by the control system of the EBW machine, the electron beam deflected to the energy-absorbing device to wait for the test, which can prevent the high power electron beam from staying on the sensor and damaging the sensor. When the test began, the beam deflected periodically. The deflection process is shown in Fig.2, in which the deflection path is along the direction of the arrow. A tungsten film with a high melting point is used as the direct contacts with the electron beam, which installed on the surface of the Faraday cup sensor. There is a pinhole in the middle of the tungsten film. The pinhole size is $\Phi 20\text{mm}$. In the deflection process the sensor collected the electron entered into the pinhole, and then the current signal formed by the electron was converted to voltage signal which was collected by the high speed data acquisition card and stored in the industrial PC.

![Fig.1. Schematic diagram of the beam quality test system.](image1)

![Fig.2. Sketch of the beam deflection.](image2)

3. Signal Acquisition
3.1 Acquisition mode and trigger source setting
The acquisition card PCI-1714 is set to post-trigger acquisition mode, which allows access to data based on a trigger event. The post-trigger acquisition starts when the PCI-1714 detects the trigger event and stops when the preset count of post-trigger samples has been acquired or when you stop the operation. For analog input operations, an external digital trigger event occurs when PCI-1714 cards
detect either a rising or falling edge on the External A/D TTL trigger input signal which is from the beam quality test system. We defined the type of trigger source as rising-edge. Fig.3 shows that the PCI-1714 begins to collect data when it detects the rising edge of the digital pulse on the A-axis. At the same time, two control signals for electromagnetic deflection coil II in Fig.1 are generated by the beam quality test system. The particular phase relationship of the two signals shown on the B-axis and C-axis in Fig.3 can make the electron beam to deflect along the path shown in Fig.2.

3.2 Signal pre-segmentation and sampling frequency

In order to ensure the signal phase relationship, only the odd signal sequence corresponding to the solid line in Fig.3 can be used for the reconstruction of the electron beam power density distribution because of the same X-coordinate of starting point of beam deflection. If all of the collected signal were used to reconstruct the three-dimensional graphic of the electron beam power density distribution, that would lead to dislocation of the spatial data points.

The entire sampling signal collected by the PCI-1714 must be pre-segmented so as to obtain each section of the signal corresponding to each beam deflection (beam from one side to another side), and thus facilitate the subsequent data processing. As the sampling clock source of the data acquisition card PCI-1714 is the same as the digital clock source used for the generation of triangular control signal in the B-axis, which is the premise of the pre-segmentation. Only the frequency division coefficient of the two clock sources is different.

The pre-segmentation is described as following steps.

Step1: The frequency of the triangular control signal in the B-axis is $f_{\text{triangle}}$. The generation of the triangular control signal is based on the direct digital synthesis (DDS).

Step2: According to sampling theorem and signal reconstruction requirements, the sampling interval is the spatial distance corresponding to the two adjacent sampling data and must be approximately equal to the corresponding pinhole diameter 20um. If the beam deflection distance in the X-direction is 20mm, the resolution in the direction can be 1000. In the controller, the sample number N for each deflection process was set to 1024, which is equal to the pulse number inputted into acquisition card PCI-1714 within the time interval $t_a$.

Step3: After data collection the pre-segmentation is carried out every 1024 digital data and the pre-segmentation signal sequence is shown on the D-axis in Fig.3. After pre-segmentation it can be seen two cases of signal on the D-axis. One case is that the output signal amplitude is zero because the electron beam does not pass the pinhole in the corresponding deflection process and the electron is not collected by the sensor. The other case is that the output signal is nearly Gaussian distribution and the electron is collected by the sensor.

![Fig.3. Diagram of the signal phase relationship.](image)
3.3 Median filtering
The median filtering is a nonlinear digital signal processing technique based on order statistics theory. It can be used to filter noise effectively [6]. The basic principle of the technique is to run through the signal data by data, replacing each data with the median of its neighborhood. The result of the median filtering is shown in Fig.4. By contrasting Fig.4(a) and Fig.4(b), we can see that the noise was removed significantly after median filtering.

![Fig.4. Median filtering.](image)

(a) Original signal with noise  (b) Filtered signal

3.4 Signal threshold segmentation
As shown in Fig.5, the three-dimensional graphics display of power density distribution of the electron beam cross-section was reconstructed with the filtered signal. It can be seen that the zero value signal occupy a large part of the signal range in the X-direction. In order to simplify the graphic display and calculation, we need to segment the signal again. The program interface for signal filtering and segmentation is shown in Fig.4(a). After pre-segmentation the signal sequence is projected onto the XOZ plane. With automatic segmentation and manual segmentation based on the signal strength threshold, we can guarantee the integrity of the signal segmentation.

![Fig.5. Signal threshold segmentation.](image)
4. Signal calibration

4.1 Spatial scale calibration

If the electron beam deflection angle is small, the deflection of the electron beam is approximately linear with the control current intensity of the magnetic field.

For the X-direction and Y-direction of electron beam deflection, the deflection length on the sensor plane (tungsten film) corresponding to two adjacent collected data can be calculated by:

\[ d_{X_i-X_{i+1}} = \frac{L_X}{N-1} \times \frac{K_X H I_{X(max)}}{N-1} \]  

(1)

\[ d_{Y_i-Y_{i+1}} = \frac{L_Y}{M} = \frac{K_Y H I_{Y(max)}}{M} \]  

(2)

Where \( L_X \) is the total deflection length in the X-direction, \( L_Y \) is the total deflection length in the Y-direction, \( H \) is the distance from the center of deflection coil to the sensor plane, \( I_{X(max)} \) is the maximum drive current in the X-direction, \( I_{Y(max)} \) is the maximum drive current in the Y-direction, \( N \) is the sample number in the X-direction, \( M \) is the stepper number in the Y-direction, \( K_X \) and \( K_Y \) are the constants which are related to the deflection coil and measured by the deflection experiment. Table 1 shows the experimental data for the determination of the deflection coil parameters.

| Deflection direction | H (mm) | \( I_{A(max)} \), \( I_{B(max)} \) (A) | Starting point (mm) | End point (mm) | \( L_X \), \( L_Y \) (mm) | \( K_X \), \( K_Y \) (A-1) |
|---------------------|-------|--------------------------------------|---------------------|----------------|----------------|-----------------|
| X                   | 330   | 1                                    | 252.532             | 272.493        | 19.961         | 0.060           |
| Y                   | 330   | 0.5                                  | 55.264              | 65.854         | 10.590         | 0.064           |

4.2 Definition of beam spot diameter

A. Amplitude definition

Firstly, taking the maximum amplitude of the beam power density as a reference data, the different percentages of the maximum amplitude \( \xi \% \) (90%, 80%, etc.) correspond to a contour respectively. As shown in Fig.6, ideal cross-section distribution of electron beam power density was Gaussian with rotational symmetry. The corresponding contour is circular, and the beam spot diameter \( d_\xi \) can be defined as the diameter of the circle. This kind of definition is the most direct method. As the actual power density distribution influenced by the characteristics of the EBW machine is non-rotationally symmetric, we need an equivalent method to define the beam spot diameter. The area surrounded by the contour \( \xi \% \) is defined as \( A_\xi \), and the equivalent beam spot diameter \( d_\xi \) is defined as the diameter of equivalent circle of the area \( A_\xi \) in (3).

\[ d_\xi = 2 \sqrt{\frac{A_\xi}{\pi}} \]  

(3)
Fig. 6. Rotational symmetrical distribution

Fig. 7. Contour plot of the power density distribution

B. Integral definition

The integral of beam power density with respect to beam cross-section area is calculated. If the integral value \( P_\lambda \) is equal to \( \lambda \% \) of the total beam power \( P_{\text{total}} \), the equivalent diameter is defined as \( d_{P_\lambda} \). The formulas are as follows.

\[
P_\lambda = \lambda \% P_{\text{total}} = \int_{A_{\lambda}} p(x, y) dA
\]

\[
d_{P_\lambda} = 2 \sqrt{\frac{A_{\lambda}}{\pi}}
\]

Where \( p(x, y) \) is the power density distribution, \( P_{\text{total}} \) is the total electron beam power.

5. Results and discussion

The beam power density distribution with the process parameters: accelerating voltage \( U_a = 150 \text{kV} \), beam current \( I_b = 15 \text{mA} \), focus current \( I_f = 360 \text{mA} \), working distance \( H = 214 \text{mm} \) is shown in Fig. 7. The distribution graph is showed by the contour. The test results show the actual beam spot diameter by the two definition methods and the beam power density distribution. The beam spot diameters of different percentage are shown in Table 2.

| \( \xi \) or \( \lambda \) (%) | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  |
|-----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \( d_\xi \) (mm)            | 0.54| 0.49| 0.44| 0.40| 0.37| 0.33| 0.29| 0.24| 0.13|
| \( d_{P_\lambda} \) (mm)    | 0.19| 0.25| 0.31| 0.36| 0.40| 0.43| 0.48| 0.55| 0.63|

The ideal power density distribution of the electron beam may take on a number of forms. The common form is the circular Gaussian distribution [7-10]. For a circular Gaussian distribution, the power density is given by,

\[
p(x, y) = \frac{\Phi_b}{2\pi\sigma_b^2} \exp\left[-\left(x^2 + y^2\right)/\left(2\pi\sigma_b^2\right)\right]
\]
In this expression, $\Phi_b$ is the total beam power, $\sigma_b$ ($\sigma_b>0$) is the standard deviation of the circular Gaussian beam, and the origin of the Cartesian coordinate is in the beam center. Considering the importance of an accurate characterization of the beam geometry, it is suggested that the equivalent beam spot diameter is considered to be a value which $\xi$ equals 10 or $\lambda$ equals 90.

For the amplitude definition, the ideal beam spot diameter ($\xi=10$) can be calculated as in (8).

$$p(x_{10},y_{10}) = \frac{\Phi_b}{2\pi\sigma_b^2} \exp\left[-\frac{(x_{10}^2 + y_{10}^2)}{2\pi\sigma_b^2}\right]$$

$$= 10\% p(x,y)_{\text{max}} = \frac{\Phi_b}{20\pi\sigma_b^2}$$

$$d_{10} = 2\sqrt{x_{10}^2 + y_{10}^2} = 7.6\sigma_b$$

For the integral definition, the integrals over the two disks can easily be computed by switching from Cartesian coordinates to polar coordinates in (10) and the ideal beam spot diameter ($\xi=90$) can be calculated as in (11).

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} p(x,y) dxdy = \int_{0}^{\pi} \int_{0}^{\xi} p(r \cos \theta, r \sin \theta) rdrd\theta$$

$$= \frac{\Phi_b}{2\pi\sigma_b^2} \int_{0}^{\pi} \int_{0}^{\xi} \exp\left(-\frac{r^2}{2\pi\sigma_b^2}\right)rdrd\theta$$

$$= \frac{\Phi_b}{2\pi\sigma_b^2} \cdot \pi \cdot \pi \sigma_b^2 \left(1-\exp\left(-\frac{\xi^2}{8\pi\sigma_b^2}\right)\right) = 90\% \Phi_b$$

$$d_{\xi90} = 2.9\sigma_b$$

It can be seen that the diameter $d_{\xi90}$ is bigger than $d_{10}$ for the ideal power density distribution from (9) and (11). The measured results $d_{10}=0.54\text{mm}$, $d_{\xi90}=0.63\text{mm}$ are not subject to the equations. The actual beam power disperse in a larger area compared to the Gaussian distribution and the measured electron beam power density distribution is not concentrated.

6. Conclusion
For the actual beam power density distribution of high-voltage electron beam welder, it is feasible to achieve the graphic reproduction of the beam power density distribution with the signal acquisition scheme and segmentation method. The noise in the signal of power density distribution can be removed effectively by median filtering. Experimental results show that with the process parameters $U=150\text{kV}$, beam current $I_b=15\text{mA}$, focus current $I_f=360\text{mA}$, working distance $H=214\text{mm}$, the measured diameter of integral definition is bigger than that of amplitude definition, but for the ideal distribution the former is smaller than the latter. The measured distribution without symmetrical shape is not concentrated compared to Gaussian distribution.
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