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Measurement of power density distribution and beam waist simulation for electron beam

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HIGHLIGHTS

- ▸ We build a framework for measuring power density distribution for electron beam.
- ▸ We capture actual electron and build transient spatial power distribution for EB.
- ▸ Tracing algorithm of power density contour for cross-section was designed.
- ▸ The volume and waist of the beam are reconstructed in 4D mode.
- ▸ Geometry measurement is finished which is befit for designing of process welding.

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ABSTRACT

The study aims to measure the power density distribution of the electron beam (EB) for further estimating its characteristics. A compact device combining deflection signal controller and current signal acquisition circuit of the EB was built. A software modelling framework was developed to investigate structural parameters of the electron beam. With an iterative algorithm, the functional relationship between the electron beam power and its power density was solved and the corresponding contour map of power density distribution was plotted through isoline tracking approach. The power density distribution of various layers of cross-section beam was reconstructed for beam volume by direct volume rendering technique. The further simulation of beam waist with all-known marching cubes algorithm reveals the evolution of spatial appearance and geometry measurement principle was explained in detail. The study provides an evaluation of promising to replace the traditional idea of EB spatial characteristics.

1. Introduction

Electron beam welding (EBW) has been used widely due to its unique advantages over other traditional fusion methods, such as high energy density, deep penetration, large depth-to-width ratio and small heat affected zone (HAZ) (Luo et al., 2010). In the nuclear energy and aerospace industries, EBW is preferred for the manufacture of high-value welds in which defects cannot be tolerated. The welds joining critical components must be reliable, consistent and reproducible (Olszewska and Friedel, 2004; Wójcicki and Mladenov, 2000). However, the process of EBW is influenced by a huge number of process parameters. The actual manufacture and design theory of an EBW electronic gun can vary. The degree of stability of an electron gun power supply system and changes that occur in vacuum can affect the electron beam diameter and the power density distribution. The geometry and quality of the weld are strongly influenced by 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, with attention to factors such as focus position, beam diameter and power density distribution. At present the beam is focused by the operator who adjusts the focus coil current settings while observing the light emitted from a target material. When the emitted light reaches a maximum intensity, the beam is considered to be focused. The reproducibility is not guaranteed. As the extremely high power density is approximately 10^7 W/cm^2 at the focus of the beam, it can melt any refractory material, which makes measurement very difficult. At the ISF-Welding Institute, Aachen University, Germany, the beam measurement system DIABEAM was developed, which provides the measurement and the three-dimensional display of

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the power density distribution across the beam diameter using an aperture diaphragm, eliminating the need for complex and cost-intensive Arata tests (Dilthey et al., 2001). The EBeam Profiler with Enhanced Modified Faraday Cup (EMFC) developed by the Lawrence Livermore National Laboratory can transfer the electron optimisation beam welding parameters for the different welding machines in different locations (Elmer and Teruya, 1998). However, the details of the finished process have rarely been reported (Dora et al., 2005; Ragheb and Zakhary, 2000; Tang and Kang, 2005).

This study aims to construct an experiment setup for sampling the current of the electron beam (EB). At the same time, relying on acquisition data, the characteristics of EB with various parameters are quantified and accurately calculated using numerical algorithms and plotted in 3D or 4D graphic modes. The reconstruction with diverse levels of high sets of cross-sections can display the micro invisible EB directly. Furthermore, the evaluation process for the spatial appearance and the location of the beam waist are elucidated.

2. Measurement setup and principle

Fig. 1 is a schematic representation of the measurement setup. The measurement device mainly consists of a deflection coil and a Faraday Cup (FC). The deflection coil enables a high-velocity EB sweep on the tungsten sensor under the deflection amplifier signal for the combined *x*-direction voltage (*Ux*) and *y*-direction voltage (*Uy*). Fig. 1. b demonstrates the voltage waveform and the relationship between *Ux* and *Uy*, which work in uniform frequency. *Ux* defines the *x*-direction step in a ladder waveform, which drives the EB to deflect by the diameter of the aperture in a line-scanning period. *Uy* is responsible for the y-direction deflection, which is controlled by a triangle waveform, and it permits the EB to sweep a come-and-go in a line-scanning period. In the first half period, the aperture signal is sampled, and in the second half period, the EB regresses to the next start sampling point without sampling. The purpose of the sample mode will be described in the following data processing section. The spatial sampling interval of the signal is the same as the diameter of the aperture. The current of the EB is measured by FC, which mainly includes a cooling cask and a tungsten sensor with an aperture. In principle, a Faraday cup is a beam stopper, isolated from the beam pipe ground potential and connected to a current meter. This device is the one unit mostly used to measure beam intensities. After the completion of scanning, the EB is placed on the cooling cask to eliminate the damage for sensor. The action of the aperture is to determine the shunted local transient cross-section current of the EB. The analogue data are processed by an amplifier circuit and a sampling circuit; then, they are stored in the buffer for subsequent signal reconstruction and calculation.

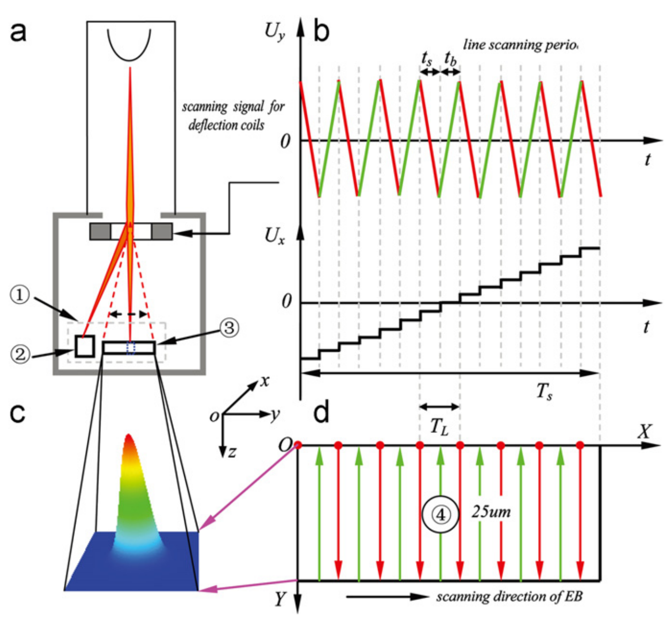

Fig. 1. Schematic diagram of measurement setup and deflection signal for data acquisition. 1. Faraday Cup with cooling cooper, sensor and signal connector. 2. Cooling water cooper used to absorb energy of EB after finishing scanning process. 3. Tungsten sensor with aperture to produce current signal of EB. 4. Aperture attached to centre of sensor.

3. Software frameworks for data processing

The frameworks for the data processing and software modules are described in Fig. 2. In addition to the measurement setup, the measurement tool has a deflection signal generator and a signal collection module. The deflection signal generator with amplifier circuit permits the EB to scan line-by-line over the sensor (Fig. 1.d). The signal acquisition module, via the variable resistor, gathers the voltage signal with a PCI-1714 card, and all collected data are then transmitted and stored in the buffer or memory. The data processing module is a core role of the measurement system, which mainly includes data pretreatment, data reconstruction and parameter analysis. The specific function is divided into signal acquisition and 3D representation, power density distribution calculation, 4D volume reconstruction and geometry measurement for the beam waist and further stages detailed in Fig. 2.

3.1. Deflection signal control and data acquisition

Due to the high power EB, to eliminate damage to the sensor, the deflection velocity must be high. In general, the deflection velocity lies in the approximate range of 200–900 m/s depending on the power level. The line sampling resolution is approximately 25 μm. Assuming a deflection velocity of 500 m/s, the sample frequency can be calculated as follows:

$$(500\ \ m/s)/(25\times10^{-6}\ \ m)=20\times10^{6}\ \ (Hz)$$

Therefore, the sampling frequency is depends on the power of the EB, the deflection velocity, the number of sampling points in a row, the number of sampling rows, and the diameter of the aperture, among other factors. To acquire the cross-section power density distribution, the EB must scan over the whole sensor area in line-by-line mode. We define the notation T_L, t_s, t_b as the line-scanning period, the period of the first half and the period of the second half (Fig. 1.b). Obviously, the relation satisfies $T_L=t_s+t_b$. In the first half line-scanning period, the signal of the EB is sampled and recorded. In the second half line-scanning period, the EB runs back to the next sampling point without sampling operation. In the *x*-direction, the EB deflects by a sampling step, and it has no movement in the *y*-direction. The location of the EB is determined by the synergic deflection control signal *Ux* and *Uy*. The purpose of the sampling mode is to avoid phase error in signal calibration. The asymmetry in the actual line-scanning sampling signal and the random location of the centre peak of the EB will lead to imprecise signal presentation.

The data acquisition of the EB is performed using the A/D converter PCI-1714 made by ADVANTECH, whose sampling frequency is up to 30 MHz and which has 12-bit analogue input resolution, to collect the amplified voltage signal of the EB. The bus-mastering DMA data transfer mode supports high bandwidth data transfer and storage. After the sampling parameter configuration,