

Electron beam characterizing and its relevance for production

Clemens Liebig, Jürgen Fath, Thorsten Löwer

Measurements of electron beam profiles always had an academic touch in the past. New standards and faster image processing make the beam characterization more and more a quality tool in production and allow transfer of beam parameters between different machines. This paper considers the latest development on using the beam diagnostic in production.

Характеризиране на електронния лъч и неговото значение за производството (Клеменс Лиебиг, Юрген Фатх, Торстен Льовер). Измерванията на профилите на електронните снопове винаги са имали академично докосване в миналото. Новите стандарти и по-бързата обработка на изображения правят характеризирането на лъча все повече и повече инструмент на качеството за производство и позволяват прехвърляне на параметрите между различните машини. Тази статия разглежда най-новото развитие на използването на диагностиката на лъча в производството.

Introduction

The beam properties of EB machines in production are influenced by many circumstances and parameters. While operating parameters such as the accelerating voltage U_a , beam current I_b , the type of cathode and the beam generating system do not vary, other influences may cause a drift of beam parameters and decreasing beam quality. Such influences are magnetic process material, inaccurately installed cathodes and deterioration of the cathode during its lifetime.

This influence is unveiled by the measurement for electron beam characterization. By analyzing the beam profile and calculating beam parameters, the quality of the beam becomes quantifiable. In case of differing beam parameters, measures can be taken to adjust the beam properties and thus to avoid wasting of expensive work pieces. Possible measures are installation of a new cathode, maintenance and removal of magnetic material and adjusting the working distance.

Electron beam parameters

The measurement of a beam profile is a possibility to reveal distortions of the beam such as misaligned or aged cathodes and deposited magnetic material. Missing parts in the profile and asymmetric profiles are the result in these cases. Aside from beam profiles, deduced beam parameters i.e. the full beam divergence angle θ and the focal beam size d_F yield useful conclusions about the beam quality and can be

used for transfer of a process between EB-machines. A plot of the beam caustic and the beam parameters is shown in Fig. 1.

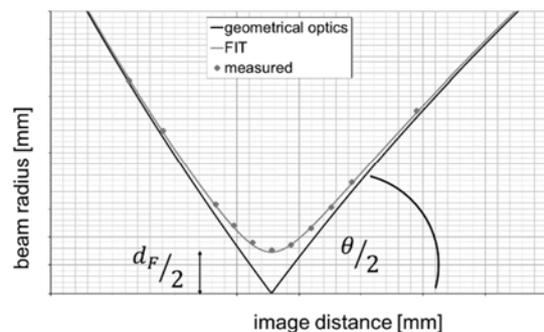


Fig. 1. Example shape of a beam caustic and the beam parameters

For determination of the beam parameters a definition of the beam size must be chosen. For specification of laser beam size, a calculation using the second order moments is well established [1]. Due to the similar applications and for comparability reasons, it seems obvious to use this standard for EB characterization as well. A beam of total beam power

$$P = \int I(x) dx$$

with the intensity distribution $I(x)$ has a diameter of:

$$d_x = 2\sqrt{2\sigma^2}.$$

For simplicity, only the one dimensional case is shown here. The two dimensional description and detailed instructions for measurement and evaluation

are available in [1]. Here, σ^2 is the second order moment of the intensity distribution with

$$\sigma^2 = \frac{1}{P} \int I(x)(x - \bar{x})^2 dx.$$

The center of mass coordinate \bar{x} calculates to

$$\bar{x} = \frac{1}{P} \int I(x) \cdot x dx.$$

To determine θ and d_F , beam profiles must be measured at at least three positions along the z-axis. Typically 10 to 20 profiles are a good compromise between accuracy and computation time. For these beam profiles the beam size is calculated and a parabola fit is carried out using the diameter squared $d^2(z)$. The minimum of the parabola represents the beam focus with $d_F(z_F)$ and the divergence is the gradient of the asymptote to $d(z)$ off the focus.

From the minimum beam diameter and the beam divergence, the beam parameter product calculates to

$$BPP = \frac{d_F \cdot \theta}{4}.$$

It is a conserved quantity for linear optics according to Liouville's theorem. Thus, by adjusting the working distance and simultaneously focusing on the surface of the work piece, the focal beam size on the surface can be chosen. By using a smaller working distance, the divergence is increased and a smaller spot size results. Adjusting the working distance can be exploited to reproduce the spot size on the surface if a process is to be transferred to a different machine.

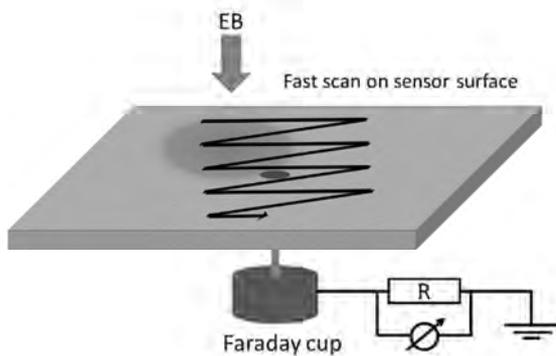


Fig. 2. Schematics of the beam profile measurement. The beam part transmitted through a small aperture is recorded together with the beam's position to obtain a beam profile

Beam profile measurement

In the case of the pro-beam sensor, to obtain two-dimensional arrays representing the beam profile, a fast scan over a small aperture is carried out using deflecting magnets in x- and y-direction. The

transmitted current is collected by a Faraday cup. By measuring the voltage while discharging and assigning it to the field of the deflecting magnets, an image of the beam profile can be built. The principle of the beam profile measurement is shown in Fig. 2. For accuracy reasons, the aperture must be sufficiently smaller than the size of the beam because a convolution of the beam profile and the aperture is recorded. A drawing of the sensor is shown in Fig. 3. Normally a 150 μm aperture made of molybdenum is used. Anyway, a correction of the convolution is reasonable. Additionally fast deflecting magnets and a thermally robust design of the sensor are required to allow measurements at 10 kW or higher beam power. The procedure is also described in [2].

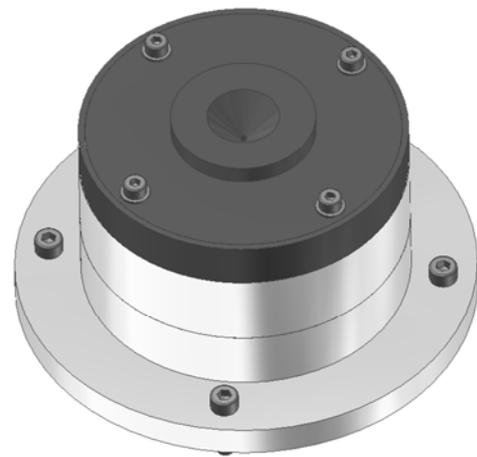


Fig. 3. Drawing of the pro-beam sensor. The signal from the isolated Faraday cup inside is passed through the grounded case for evaluation

For beam characterization, beam profiles at different z-positions are required. Instead of moving the sensor, the magnetic lens current is scanned. This is a simple and fast alternative to moving the sensor and yields accurate results for a sufficiently high working distance.

Capturing of one beam profile takes less than 1 s with a reasonable image size and resolution. The algorithm developed at pro-beam for the beam parameter measurement saves the desired number of profiles and does the necessary calculations automatically. This includes background subtraction, the parabolic fit and presentation of the resulting beam profiles and parameters. Calculation time on modern computers is sufficiently low to carry out the full measurement program in less than five minutes. Hence, the time needed for use of this diagnostics tool is determined mainly by the time for connecting the sensor and evacuation of the vacuum chamber.

Alternative sensor designs and algorithms for beam profile evaluation have been developed in the past. An example is explained in [3].

Fig. 4 shows the result screen presenting data to the user after the beam profile measurement. Beam profiles around the focal spot can be seen on the left side of the screen. The caustic together with the most essential deduced parameters can be seen on the right.

Additionally to the beam characterization, 3D-FEM-simulations have been carried out for some electron gun setups. A comparison of the resulting beam parameter product is shown in Fig. 5. The measured BPP is around 20% higher than the simulation data for the peak used beam power. This can be due to misalignment. A correction of the beam profile convolution with the circular shaped sensor aperture of 150µm diameter is included.

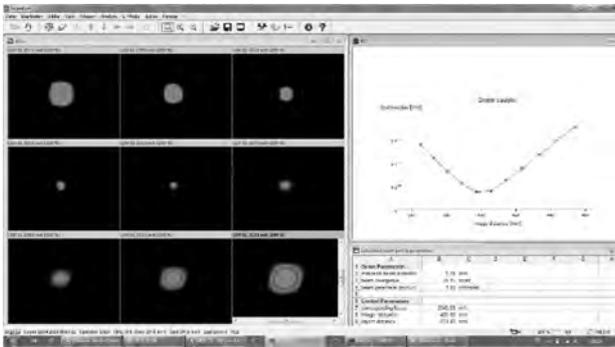


Fig. 4. Result screen of the measurement program showing a series of beam profiles and deduced data.

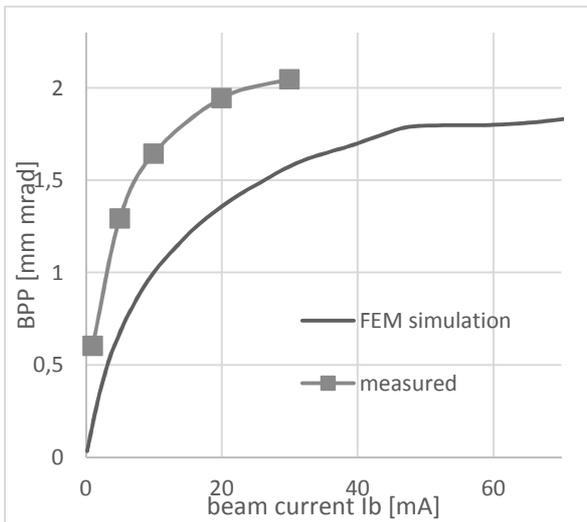


Fig. 5. Measured beam parameter product depending on the beam current and calculated BPP from 3D-FEM-simulations. Aside from the beam power, the achievable BPP depends on the gun geometry, the accelerating voltage, cathode age and alignment and many further parameters. A correction of the beam profile convolution is included

Application in production

For series production using EB welding, it is desirable to reproduce a certain shape of the weld seam which is approved and guaranties high quality. The shape of the weld seam i.e. its depth and width strongly depend on the surface spot size. Deeper welds may also be influenced by the divergence angle but the achievable focal beam size d_F is essential. However d_F is determined by the beam parameter product which in turn does not change after generation of the beam i.e. after passing the anode. Using a different gun while operation parameters such as beam power, working distance, focal offset etc. are held constant can lead to a totally different seam depth and changed shape. An example is shown in Fig. 6. Two different beam generators have been used for sample welds at identical accelerating voltage. The right side weld is 20% deeper and significantly narrower. If a production process is to be transferred to a new EB-machine, a measurement of the beam parameters on both machines can yield valuable information of how to choose the correct working distance. For most EB-welding machines which possess only one magnetic lens this is the only parameter which allows an adaption of the beam focus size on the work piece.



Fig. 6. Cross section of two EB welds with 3 kW beam power and different surface spot size

This follows directly from the beam parameter product being a conserved quantity and its definition.

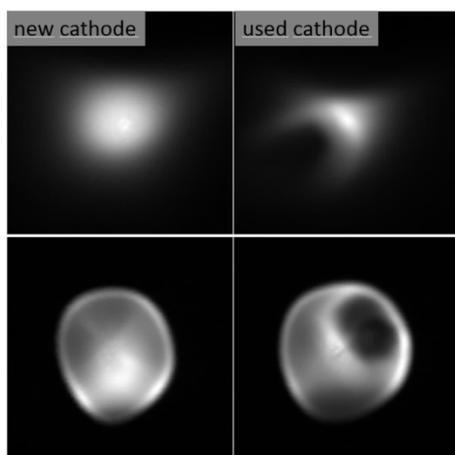


Fig. 7. Example beam profiles 30 mm in front of and behind the focal spot for a 2 kW beam of 24 mrad full divergence angle

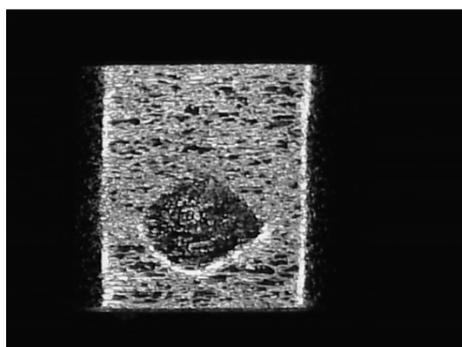


Fig. 8. Surface of a used cathode providing a lower quality beam

Verification of beam quality after maintenance, cathode change and generally before welding of expensive parts is a second application for beam characterization in production. Arcs and bombardment with ionized process gas contribute to deterioration of the cathode surface. Beam profiles as shown in Fig. 7 for the used cathode in Fig. 8 are a possible result and affect beam parameters as well.

Aside from these applications in production, electron beam characterization is a powerful tool in research. It allows investigations on how the beam properties must be chosen to achieve optimum processing results.

Conclusions

Beam profile measurement will be used increasingly for beam quality verification in acceptance tests for new guns and before and after maintenance of the machines operated for job order production.

The possibility of transferring a process easily to another machine offers higher flexibility and saves time formerly needed for process adjustment.

Achievements that have been made are the fast and

automatic execution and excellent resolution due to the small aperture diameter. Additionally, using the second order moment as beam size definition offers high sensitivity to changes of the beam profile while the pro beam's elaborate algorithms for treatment of noise and static background guarantee low systematic errors.

Remaining challenges are operation of the beam profile measurement on older machines or machines not operated with a pro-beam gun and control system. Therefore, the development of a standalone beam profile measurement system is planned. It is going to include a CNC, PC and function generator and hence only requires connectivity to the magnet power supplies and a feed through for the sensor signal.

REFERENCES

- [1] ISO 11146-1:2005, "Lasers and laser-related equipment -- Test methods for laser beam widths, divergence angles and beam propagation ratios -- Part 1: Stigmatic and simple astigmatic beams".
- [2] C. Menhard, T. Löwer, „Die Elektronenstrahlgeometrie - Definition, Vermessung und Bedeutung für den Schweißprozess“, pro-beam AG & Co. KGaA, Schweißen und Schneiden 61, 2009.
- [3] J. Elmer, A. Teruya, D. O'Brien, "Tomographic Imaging of Noncircular and Irregular Electron Beam Current Density Distributions", *Welding Research*, 72 (11), 1993, pp. 492-s.

Dr. Clemens Liebig – Was born in Worms, Germany in 1984. He studied physics at TU Darmstadt, Germany and received his PhD in accelerator physics from Universität Hamburg/DESY, Germany in 2014. Since 2015 he is working as a development engineer at pro-beam AG & Co. KGaA on beam profile measurement, X-ray imaging, FE simulations and other beam physics related topics.

Tel.: +49(0)89/899233 49;
e-mail: clemens.liebig@pro-beam.com

Jürgen Fath – Was born in Ingolstadt, Germany in 1976. He studied physics at TU München, Germany. Since 2003 he is working as a development engineer at pro-beam AG & Co. KGaA on beam profile measurement, automatic beam alignment, seam tracking and other electron optics related topics.

Tel.: +49(0)89/899233 30;
e-mail: juergen.fath@pro-beam.com

Dr. Thorsten Löwer by education physicist. As a scientist he had worked at the Max-Planck-Institute of Quantenoptics in Munich. After that time he is in charge of the development of electron beam equipment for welding, drilling and surface treatment. Today he is member of the board in the company pro-beam.

Tel.: +49(0)89/899233 25;
e-mail: thorsten.loewer@pro-beam.com