Electron beam characterization by a tomographic approach

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Abstract. In this paper, experimental data are analyzed for the integral current density distribution when the electron beam parameters are varied, namely, focusing current, beam current, venelt voltage and the distance to the measuring device. The 3D beam radial current density distribution is reconstructed by implementing a tomographic approach. The characterization of the electron beam is considered in connection with the estimation of the following parameters: the radial and the angular beam distribution standard deviations, the position of the beam focus and the beam emittance.

1. Introduction

The characterization of the radial and the angular space distributions of particle trajectories (or the respective current distributions) in powerful electron beams is an important scientific and practical task, connected with improving the quality of the electron beam technologies, developing standards for electron beam welding machines and permitting transfer of a concrete electron beam welding technology from one equipment to another. To apply the advantages of electron beam welding, it is necessary to know the properties of the electron beam. There only exist standards for measurements of the electron beam current and accelerating voltage as beam characteristics, applicable to the acceptance inspection of an electron beam welding machine or in research. These parameters cannot characterize the quality of the electron beam in terms of the ability to be transported over long distances and to be focused into a small spot with a minimum of divergence.

Tomography is a technique for reconstruction of a two-dimensional object image from a set of its one-dimensional projections, measured as an array of line integrals (or slices) of the object studied. This technique is widely used in different scientific areas, starting from medical applications, material sciences etc. A Fourier transform from real to frequency space and a consequent inverse Fourier transform permits to reconstruct the beam cross-section current density image (beam radial intensity profile) with its asymmetry features. In the last decade, profile measurement of intense electron beams by an enhanced modified Faraday cup was proposed. We developed further this tomography evaluation to obtain the emittance of the beam, containing the current distribution of the beam in the studied cross-section, together with the angular distribution of the beam electrons. The emittance (or its reciprocal value – the brightness normalized to one volt) is an invariant value along the beam.
and could be used as a standard characteristic, for prognosis and optimization, as well as for transfer of technologies from one electron beam equipment to another.

Measurements of the accelerating voltage, beam current, focus coil current, and vacuum level provide little insight into the characteristics of the electron beam used for welding. The profile of the beam has been monitored lately by the enhanced modified Faraday cup (EMFC) diagnostic tool, proposed by J. Elmer and co-workers [1,2]. The benefit of integrating this diagnostic tool into future process control regimes is that the beam radial current distribution characteristics, as the peak power density, full width at half maximum and full width at 1/e^2 values, can be quantified. The results show that machine performance, in terms of these measured beam characteristics, varies over time. Testing has shown that the variability of the beam characteristics can be considerably decreased by using the EMFC diagnostic tool. With the implementation of this diagnostic tool in the process control procedures, every electron beam weld in approximately 90 welds over an 18-month time frame, met all of the requirements defined in the weld process specification and passed all of the post-weld quality control checks [3].

For the weld quality assurance, the right choice is important of the beam focus position with respect to the work-piece surface. The interaction of the beam with the welded material, different for various metals and for changed beam focus positions, is a limiting factor in guaranteeing the right choice of the sharp focus by a subjective operator’s decision. The visualization and focusing of the beam spot could be done by directing the beam on a block of refractory metal. When the metal becomes hot, the operator adjusts the beam focusing current until the spot’s optical brightness appear to be at maximum. The sharp focus beam position, evaluated more precisely by EMFC in the absence of beam-sample metal interaction, is also inapplicable to controlling the electron beam welding due to changes arising from beam scattering and from gas focusing of beam electrons in the metal vapors and the generated plasma in the interaction beam/metal-work-piece zone [4, 5].

There are several approaches for electron beam characterization [6-17], but generally they are divided into two big groups: i) assuming a Gaussian distribution of the beam current density and ii) without this assumption.

The measurement technique, using a Faraday cup and few radial slits in a disc, on which the monitored electron beam is rotated, in fact measures the integrated electron beam radial current density distributions by integrating the current passing along these thin slits in projections of the beam intensity, taken at equally spaced angles around the beam (figure 1).

![Figure 1. Tomographic approach – measurement of integral current densities at different angles and obtaining a set of radial distribution images in the frequency domain for each angle θ.](image)

To apply the computer tomographic approach for estimation of the radial current density distribution, a refractory metal disk (W) with several radial slits is needed. The voltage signal is measured and the integral radial current density distributions are determined at the different angles of the slits (see figure 2 and figure 3).
2. Experimental conditions
Our measuring devise had eight slits, two of them situated perpendicularly to each other:
a) $\theta = 0^\circ$; b) $\theta = 51^\circ$; c) $\theta = 90^\circ$; d) $\theta = 102^\circ$; e) $\theta = 153^\circ$; f) $\theta = 204^\circ$; g) $\theta = 255^\circ$; h) $\theta = 306^\circ$.

The integral current density distributions at different angles were obtained when the following parameters were varied:
$I_f$ – focusing current, $I_e$ – the beam current, $U_v$ – venelt voltage (see table 1). This set of experiments was repeated for three values of the distance to the measuring device $H$ – 330 mm, 340 mm and 350 mm, measured from the top of the vacuum chamber (72 experiments). The electron beam installation had a power of 2 kW, the pressure in the vacuum chamber being $7 \times 10^{-5}$ hPa. The tungsten disc used was 4 mm thick and the slit width was 0.1 mm.

Figure 4 presents the experimental signal for experiment No. 3 (table 1) at $I_f = 221$ mA, $I_e = 6$ mA, $U_v = -50$ V and $H = 350$ mm.

3. Radial current density distribution image reconstruction
Based of the tomographic approach, the 3D beam radial current density distribution was reconstructed from its one-dimensional (1-D) projections in three cross-sections of the electron beam:

$$j_\rho(\theta, t) = \int_{-\infty}^{+\infty} j(x, y)dz.$$
Figure 4. The experimental signal for experiment No. 3, \( H = 350 \) mm and degrees: 1 - 0°; 2 - 51°; 3 - 90°; 4 - 102°; 5 - 153°; 6 - 204°; 7 - 255°; 8 - 306°.

The \( t \) axes coincide with the slices of the measuring device situated at different measurement angles \( \theta \) (see figure 1). The collection of these projection functions at all angles \( \theta \) is called Radon transform. In order to reconstruct the images, the Fourier slice theorem was used. The slice theorem proves that the 1D Fourier transform of the projection function \( j_p(\theta, t) \) is equal to the 2D Fourier transform of the image evaluated on the line that the projection was taken on.

The algorithm implemented was the following [18-20]:

**Step 1.** Obtaining 1-D projections of a 2-D radial current density distribution at all possible angles in three cross-sections of the electron beam.

**Step 2.** Processing 1-D projections of a 2-D radial current density distribution at all possible angles in three cross-sections of the electron beam (Radon transform, digital signal processing).

**Step 3.** 1-D Fourier transform of the obtained projections to the frequency domain for each cross-section of the beam.

**Step 4.** Filtering the signals – by direct convolution or using the fast Fourier transform.

**Step 5.** Interpolation in the frequency domain.

**Step 6.** Initial image reconstruction by inverse 2D Fourier transform.

**Step 7.** 3D current density distribution modeling using the reconstructed images in three cross-sections of the beam – implementing spline-functions.

Figure 5 shows the reconstructed radial current density distributions in 2D and 3D view for \( I_t = 221 \) mA, \( I_e = 2 \) mA, \( U_v = -50 \) V (experiment 1, table 1) and \( H = 330 \) mm as an illustration of the implementation of the algorithm described.

Figure 5. the reconstructed radial current density distributions in 2D (a) and 3D (b) view for \( I_t = 221 \) mA, \( I_e = 2 \) mA, \( U_v = -50 \) V (experiment 1, table 1) and \( H = 330 \) mm.
4. Electron beam characterization
Initially, for each of the beam cross-sections and each of the electron beam parameters set (table 1), some beam current density characteristics were calculated (table 2) using the data obtained from the measuring device, consisting of a tungsten entrance disc with radial slits and a Faraday cup, (shown on figure 2) and utilizing our computer program.

Table 2. Electron beam current density characteristics.

| No. | \(d_{b,1}\) | \(\sigma_1\) | \(j_{xy,1}\) | \(j_{\theta,\text{max},1}\) | \(d_{b,2}\) | \(\sigma_2\) | \(j_{xy,2}\) | \(j_{\theta,\text{max},2}\) | \(d_{b,3}\) | \(\sigma_3\) | \(j_{xy,3}\) | \(j_{\theta,\text{max},3}\) |
|-----|------|------|------|------|------|------|------|------|------|------|------|------|
| 1   | 5.2  | 0.77 | 0.2976| 0.1720| 6    | 0.80 | 0.3184| 0.1560| 6.8  | 1.26 | 0.2400| 0.0920 |
| 2   | 5.6  | 0.63 | 0.3184| 0.2120| 6.8  | 0.68 | 0.9696| 0.5600| 5.6  | 0.85 | 0.9280| 0.4640 |
| 3   | 5.2  | 0.82 | 1.1264| 0.5600| 5.2  | 0.52 | 1.1600| 0.9000| 5.2  | 0.68 | 0.9920| 0.6400 |
| 4   | 4.8  | 0.67 | 0.1472| 0.0820| 4.8  | 0.64 | 0.3024| 0.1920| 4.4  | 0.44 | 0.0762| 0.0600 |
| 5   | 6.8  | 0.68 | 0.7360| 0.5140| 4.0  | 0.63 | 0.8992| 0.6160| 5.2  | 0.52 | 0.3968| 0.3200 |
| 6   | 6.0  | 1.05 | 0.8140| 0.8920| 4.4  | 0.79 | 1.3230| 0.6200| 8.4  | 0.84 | 1.2768| 0.7280 |
| 7   | 3.6  | 0.55 | 0.1848| 0.1320| 4.4  | 0.52 | 0.2368| 0.1720| 5.6  | 0.56 | 0.0845| 0.0576 |
| 8   | 5.2  | 0.52 | 0.5120| 0.4920| 4.4  | 0.75 | 0.6112| 0.3440| 7.6  | 0.76 | 0.3600| 0.2000 |
| 9   | 3.2  | 0.48 | 0.9600| 0.7520| 4.0  | 0.67 | 1.7680| 1.0200| 9.2  | 0.92 | 0.6016| 0.3440 |
| 10  | 3.6  | 0.55 | 0.1208| 0.0980| 2.8  | 0.43 | 0.2368| 0.2200| 8.4  | 1.56 | 0.0960| 0.0288 |
| 11  | 7.2  | 0.97 | 0.6528| 0.2720| 6.4  | 0.64 | 0.7208| 0.6720| 9.2  | 1.35 | 0.4715| 0.3560 |
| 12  | 3.6  | 0.38 | 0.7968| 0.7760| 2.8  | 0.42 | 0.9364| 0.9600| 8.0  | 0.80 | 0.3772| 0.2400 |
| 13  | 6.4  | 0.84 | 0.1699| 0.0800| 5.2  | 0.94 | 0.2640| 0.1240| 4.8  | 0.80 | 0.7960| 0.6400 |
| 14  | 6.8  | 1.27 | 0.6272| 0.2880| 6.0  | 0.86 | 0.7392| 0.3920| 4.0  | 0.69 | 0.3936| 0.2240 |
| 15  | 4.8  | 0.70 | 1.2288| 0.7200| 5.6  | 1.00 | 1.3440| 0.5400| 6.0  | 0.86 | 0.8928| 0.4000 |
| 16  | 4.4  | 0.77 | 0.1872| 0.0940| 5.2  | 0.57 | 0.3336| 0.2440| 5.2  | 0.52 | 0.0930| 0.0824 |
| 17  | 4.8  | 0.59 | 0.6208| 0.4560| 6.0  | 0.71 | 0.6752| 0.4000| 6.0  | 0.84 | 0.3288| 0.1600 |
| 18  | 5.6  | 0.63 | 1.2544| 0.8160| 6.4  | 0.75 | 1.1120| 0.5400| 3.6  | 0.55 | 0.4512| 0.3480 |
| 19  | 7.6  | 0.76 | 0.2512| 0.2100| 4.0  | 0.56 | 0.2336| 0.1560| 7.2  | 1.28 | 0.1531| 0.0712 |
| 20  | 6.8  | 0.68 | 0.5760| 0.4160| 5.6  | 0.56 | 0.9376| 0.8320| 4.8  | 0.53 | 0.1094| 0.0912 |
| 21  | 6.0  | 0.63 | 1.2960| 0.8160| 2.8  | 0.52 | 1.1520| 0.8400| 5.6  | 1.05 | 0.6768| 0.3560 |
| 22  | 3.6  | 0.37 | 0.1304| 0.1420| 3.6  | 0.46 | 0.2304| 0.2120| 5.2  | 0.61 | 0.1066| 0.0824 |
| 23  | 6.4  | 0.88 | 0.4128| 0.2280| 7.2  | 0.72 | 1.0368| 0.6480| 6.8  | 1.13 | 0.5936| 0.2680 |
| 24  | 6.4  | 0.94 | 0.8928| 0.3840| 4.4  | 0.72 | 1.0484| 0.8600| 4.4  | 0.51 | 0.3968| 0.3440 |

The signal range, corresponding to the beam diameter, was calculated as:

\[ R = x_{\text{max}} - x_{\text{min}} = d_b. \]

The double indefinite integral of the radial beam current density distribution, integrated over \(x\) and \(y\), and representing the beam current, is:

\[ j_{xy} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} j(x, y) \, dt \, dz, \]

\(\sigma\) is the standard deviation (beam radius on half maximum of signal); \(j_{\theta,\text{max}}\) is the maximum value of the integral current density distribution, as measured for each of the beam cross-sections and each of the electron beam parameters set. The values for the standard deviation \(\sigma_i\) are estimated by minimization of the following loss function:

\[ Q_{\sigma} = \sum_{i=1}^{n} (j_{\theta} - \hat{j}_{\theta})^2, \]
where \( j_a(t) \) and \( \hat{j}_a(t) \) are correspondingly the observed and estimated discrete (from 1 to \( n \)) values for every individual integral signal of the radial electron beam current distribution.

Assuming symmetrical current density distribution and averaging the results presented in table 2 for all measurement angles, estimation of the beam focus position, the radial and angular standard deviations \( \sigma_{oi} \) and \( \sigma'_{oi} \), using the equation:

\[
(\sigma_{oi})^2 = (\sigma_{oi})^2 + (z_{oi} - z_o)^2 (\sigma'_{oi})^2,
\]

written under the condition of zero value of the co-variance between \( x \) and \( x' \) in the canonic position of the emittance diagram, one can find \( \sigma_{x,oi} \) at measured \( \sigma_{xi} \). Since \( \sigma_{ii}^2 = \sigma_{oi}^2 + \Delta_{o-i}^2 \sigma_{oi}^2 \), then:

\[
\sigma_{oi}^2 = \frac{\sigma_{ii}^2 - \sigma_{oi}^2}{\Delta_{o-i}^2}.
\]

The emittance and the standard deviations are related:

\[
\varepsilon = C \sigma_{o} \sigma'_{o},
\]

where the coefficient \( C \) can be calculated as:

\[
C = [-2 \ln(1 - p)]^{1/2}.
\]

For value of the coefficient equal to 9, the whole beam current is considered (without reduction of the part of the beam current \( p = I_m / I_b \), for example, to 80%).

**Table 3.** Electron beam characteristics.

| No. | \( H_{focus} \) [mm] | \( \sigma_0 \) [mm] | \( \sigma'_0 \) [mm.mrad] | \( \varepsilon \) [mm.mrad] |
|-----|------------------|------------------|------------------|------------------|
| 1   | 334.48           | 0.71             | 0.0671           | 0.4282           |
| 2   | 331.63           | 0.63             | 0.0312           | 0.1763           |
| 3   | 341.77           | 0.51             | 0.0545           | 0.2506           |
| 4   | 332.78           | 0.68             | 0.0297           | 0.1806           |
| 5   | 324.26           | 0.69             | 0.0175           | 0.1080           |
| 6   | 343.54           | 0.77             | 0.0529           | 0.3654           |
| 7   | 339.26           | 0.52             | 0.0194           | 0.0908           |
| 8   | 345.55           | 0.77             | 0.0372           | 0.2605           |
| 9   | 322.79           | 0.43             | 0.0299           | 0.1155           |
| 10  | 335.50           | 0.23             | 0.1088           | 0.2296           |
| 11  | 337.73           | 0.60             | 0.0986           | 0.5321           |
| 12  | 334.26           | 0.32             | 0.0465           | 0.1356           |
| 13  | 339.22           | 0.94             | 0.0459           | 0.3887           |
| 14  | 349.32           | 0.69             | 0.0552           | 0.3424           |
| 15  | 341.62           | 1.01             | 0.0621           | 0.5614           |
| 16  | 347.55           | 0.51             | 0.0327           | 0.1511           |
| 17  | 300.71           | 0.39             | 0.0151           | 0.0531           |
| 18  | 338.89           | 0.75             | 0.0461           | 0.3121           |
| 19  | 336.66           | 0.47             | 0.0891           | 0.3806           |
| 20  | 347.82           | 0.53             | 0.0241           | 0.1144           |
| 21  | 336.32           | 0.45             | 0.0692           | 0.2824           |
| 22  | 326.29           | 0.36             | 0.0207           | 0.0675           |
| 23  | 337.52           | 0.70             | 0.0712           | 0.4475           |
| 24  | 369.16           | 0.25             | 0.0231           | 0.0526           |
The transformations of coordinate $x$ and $x'$ in the draft space (that is free from forces external to the beam) are given in a matrix expression as:

$$
\begin{pmatrix}
  x \\ x'
\end{pmatrix}
_2 =
\begin{pmatrix}
  1 & L \\ 0 & 1
\end{pmatrix}
\begin{pmatrix}
  x \\ x'
\end{pmatrix}
_1.
$$

There index 1 stands for the cross-section at $z = z_1$ before the draft region with length $L$, and index 2, at $z = z_2$, $L$ is the distance between these two cross-sections, measured along the beam axis.

The results calculated for the focus position ($H_{\text{focus}}$) measured with respect to the top wall of the vacuum chamber, the radial ($\sigma_o$) and the angular ($\sigma_{\alpha}'$) standard deviations and the emittance value are presented in table 3. The average of the emittance values is 0.2511.

5. Conclusions

The management of the electron beam welding quality directed to optimizing the process parameters is an important way to improve the use of the expensive equipment and to make the EBW process more efficient in terms of consuming materials, time and energy.

The beam emittance, as well as the beam profile, are significant and appropriate characteristics of the beam quality. The measurement of these characteristics will: (i) assist in standardizing the electron optical systems, (ii) provide adequate conditions for welding production quality control by keeping a high reproducibility of the welds (iii) support the attempts to transfer a concrete technology from one welding machine to another and (iv) assist in implementing expert systems for the operator’s choice of suitable regimes for producing desirable welds.

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