Emittance – quantitative characteristic of welding beam quality

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

The beam emittance as well as the electron beam density distribution are significant and appropriate characteristics of the beam quality. The measurement of these characteristics will: (i) help standardization of 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 the concrete welding technology from one welding machine to another and (iv) at creating expert systems for an operator choice of suitable regimes for gaining desirable welds.

Емитанс – количествена характеристика на качеството на електронния лъч при заваряване (Елена Колева, Георги Младенов, Володя Джаров, Димитър Тодоров, Марин Карджиев, Лиляна Колева). *Управление на качеството по време на електроннолъчево заваряване, насочено към оптимизиране на параметрите на процеса е важен начин за подобряване на скъпото оборудване и за повишаването на ефикасността на процеса по отношение на изразходваните материали, време и енергия.*

Емитансът на електронния лъч, заедно с плътността му на разпределение са значими и подходящи характеристики на качеството на лъча. Измерването на тези характеристики ще: а) спомогне за стандартизирането на електтронно оптичните системи, б) ще осигура адекватни условия за управлението на качество на заваръчното производство, чрез осигуряване на висока възпроизводимост на шевовете, в) ще допринесе за опитите за пренасяне на конкретна заваръчна технология от една заваръчна машина към друга и г) ще допринесе и за създаването на експертни системи за избор на оператора на подходящи режими за получаването да желаните заваръчни шевове.

Introdiction

The knowledge of radial current distribution in one beam cross-section plane is not enough to characterize the beam/work-piece interaction along the beam penetration depth. Better understanding and ability to prognostication is simultaneously evaluation of radial and angular distribution of the beam electrons. The electron beam emittance is chosen as a suitable parameter for standardization of the electron optical technology systems. The evaluation of this parameter is a condition for achieving good quality, repeatability and reproducible performance of electron beam welds. This parameter forms the basis for transferring a concrete technology from one machine to another which will minimize the volume of preliminary experimental tests to adjust satisfactory regime parameters as well as will extend the capability of the expert systems to choose the process regimes of specific welds. In previous authors papers [1-10] the methods for intense beam emittance evaluation were analyzed. A new method for emittance determination utilizing three beam profile measurements along the beam axis was proposed. Another method using the changes of the beam focusing current during the beam profiles measurement utilizing non-movable modified Faraday cup was also developed.

In one axial-symmetrical beam under use is the plane rr' and here every trajectory can be presented by a point of coordinates - radius r (namely distance between electron trajectory and beam axis) and divergence or convergence angle of trajectory to the normal of beam axis $r'=(dr/dz)$. The *emittance* is the divided to π area of the region on the plane rr' where are situated the points, representing the particles of the beam. The stationary particles distribution function in one monochromatic stream there four variables: x,y,x',y' . For the geometry presentation more suitable is to use two-dimensional projections xx' and yy'. Here the sign ' means the first derivative of corresponding value taken on the distance measuring along beam z (x' = dx/dz ; y' = dy/dz). There projections, together with the beam cross section are able to give sufficient visual aid.

The emmittance is a quality characteristics of the beams that determine the non-laminarity of the particle trajectories in the beam. Less emmittance value means higher brightness of the beam. As general, the emittance diagram is elliptical and inclination of ellipse axis demonstrated the convergent or divergent beam trajectories. For real electron beams the emittance is always larger than 0. In these beams the beam region is not clearly limited, the distribution of the points of the diagram in the plane rr' id not uniform, and it has decreasing density near the boundary region. Then, for the definition of the emittance the area, which contain a certain part of these points, e.g. 90% is used.

Since the numerical value of the emittance depends on the velocity of the electrons V_z in the movement direction often it is used the characteristic *normalized emittance* [12,13]:

$$\varepsilon_n = \left(\frac{V_z}{c}\right)\varepsilon ,$$

where c is the velocity of light.

From the Liouville's theorem considering the movement of particles in the phase space (the space of the coordinates and the impulses of movement of the particles) follows that the value of the normalized emittance should not change along the whole length of the beam. This is true only for ideal systems without aberrations and non-homogeneities, as well as without collisions between the electrons and the particles of the environment and interaction between separate electrons.

Radial current density distribution image reconstruction

Our measuring devise has eight slits, and two of them are situated perpendicularly to each other [14,15]:

a) $\theta = 0^o$; b) $\theta = 51^o$; c) $\theta = 90^o$; d) $\theta = 102^o$; e) $\theta = 153^o$; f) $\theta = 204^o$; g) $\theta = 255^o$; h) $\theta = 306^o$.

Integral current density distributions at different angles are obtained at variation of the parameters: I_f – focusing current, I_e – the beam current, U_v – venelt voltage. 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 is 2 kW and the pressure in the vacuum chamber is $7{*}10^{-5}$ hPa. The tungsten disc that is used is 4 mm thick and the slit width is 0.1 mm.

On Fig. 1 the experimental signal for I_f = 221 mA, I_e = 6 mA, U_V = -50 V and H = 350 mm is presented.

On the base of the tomographic approach the 3D beam radial current density distribution is reconstructed from its one-dimensional (1-D) projections in three cross-sections of the electron beam:

$$j_\theta(\theta,t) = \int_{-\infty}^{+\infty} j(x,y)dz$$

The *t* axes coincide with the slices of the measuring device situated at different measurement angles θ. The collection of these projection functions at all angles θ is called Radon transform. In order to reconstruct the images the Fourier Slice Theorem is used. The Slice Theorem defines that the 1D Fourier Transform of the projection function $j_\theta(\theta,t)$ is equal to the 2D Fourier Transform of the image evaluated on the line that the projection was taken on.

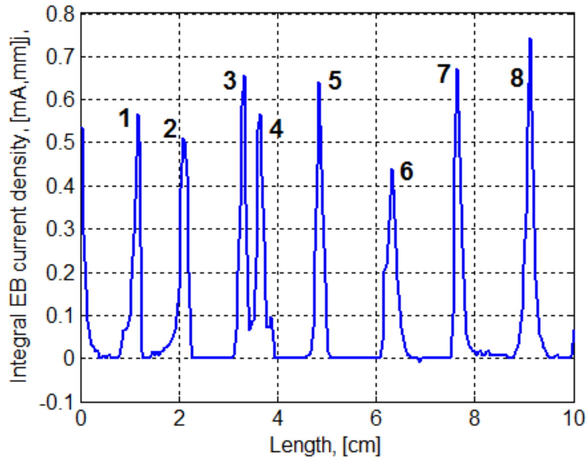

Fig.1. The experimental signal for experiment №3, H=350 mm and degrees:
1 - 0°; 2 - 51°; 3 - 90°; 4 - 102°; 5 - 153°; 6 - 204°; 7 - 255°; 8 - 306°

The implemented algorithm is the following [16-18]:

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

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

Step 3. 1-D Fourier transform of the obtained projections to 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.

On Fig. 2 are shown the reconstructed radial current density distributions in 2D and 3D view for I_f = 221 mA, I_e = 2 mA, U_v = -50 V and H = 330 mm as an illustration of the implementation of the described algorithm.

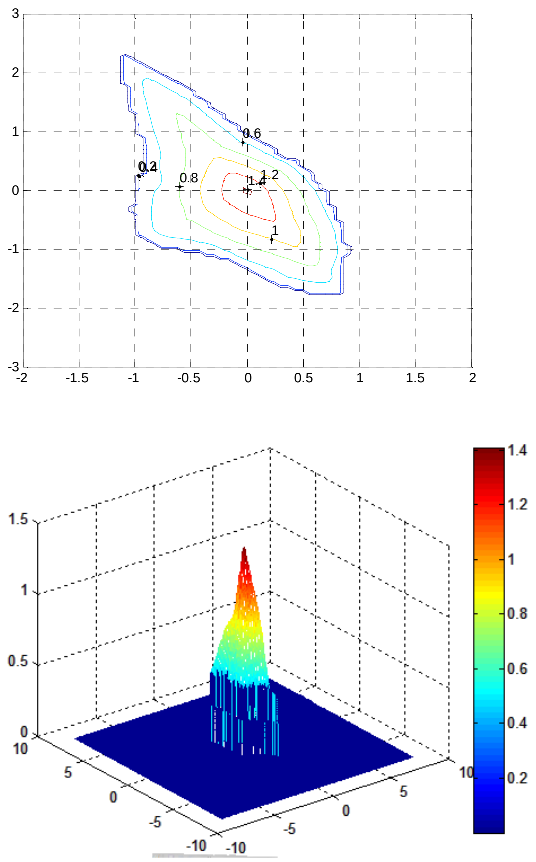

Fig. 2. The reconstructed radial current density distributions in 2D (a) and 3D (b) view for I_f=221 mA, I_e=2 mA, U_v = -50 V and H=330 mm

Electron beam characterization

Initially, for each of the beam cross-sections and each of the electron beam parameters set some beam current density characteristics are calculated [15], using the data obtained from the measuring device, consisting of tungsten entrance disc with radial slits and a Faraday cup, and utilizing our computer program.

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

$$R = x_{\max} - x_{\min = d_b}$$

Double indefinite integral of the radial beam current density distribution, integrated by x and y, and representing the beam current, is:

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

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

$$Q_\alpha = \sum_{i=1}^{n} (j_{\theta i}(t) - \hat{j}_{\theta i}(t))^2$$

where $j_{\theta i}(t)$ and $\hat{j}_{\theta i}(t)$ 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 σ_{oi} and σ'_{oi}, using the equation:

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

written at a 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 σ_{xi}. Since $\sigma_i^2 = \sigma_{oi}^2 + \Delta_{o-i}^2 \sigma_{oi}'^2$, then:

$$\sigma_{oi}'^2 = \frac{\sigma_i^2 - \sigma_{oi}^2}{\Delta_{o-i}^2}$$

The emittance and the standard deviations are related:

$$\varepsilon_p = C \sigma_o \sigma'_o$$

where the coefficient C could 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 1

Electron beam characteristics

№	I_f [mA]	I_e [mA]	U_v [V]	H_{focus} [mm]	σ_0 [mm]	σ'_0 [mrad]	ε [mm.mrad]
1	221	2	-50	334.48	0.71	0.0671	0.4282
2	221	4	-50	331.63	0.63	0.0312	0.1763
3	221	6	-50	341.77	0.51	0.0545	0.2506
4	225	2	-50	332.78	0.68	0.0297	0.1806
5	225	4	-50	324.26	0.69	0.0175	0.1080
6	225	6	-50	343.54	0.77	0.0529	0.3654
7	229	2	-50	339.26	0.52	0.0194	0.0908
8	229	4	-50	345.55	0.77	0.0372	0.2605
9	229	6	-50	322.79	0.43	0.0299	0.1155
10	233	2	-50	335.50	0.23	0.1088	0.2296
11	233	4	-50	337.73	0.60	0.0986	0.5321
12	233	6	-50	334.26	0.32	0.0465	0.1356
13	221	2	-40	339.22	0.94	0.0459	0.3887
14	221	4	-40	349.32	0.69	0.0552	0.3424
15	221	6	-40	341.62	1.01	0.0621	0.5614
16	225	2	-40	347.55	0.51	0.0327	0.1511
17	225	4	-40	300.71	0.39	0.0151	0.0531
18	225	6	-40	338.89	0.75	0.0461	0.3121
19	229	2	-40	336.66	0.47	0.0891	0.3806
20	229	4	-40	347.82	0.53	0.0241	0.1144
21	229	6	-40	336.32	0.45	0.0692	0.2824
22	233	2	-40	326.29	0.36	0.0207	0.0675
23	233	4	-40	337.52	0.70	0.0712	0.4475
24	233	6	-40	369.16	0.25	0.0231	0.0526

The transformations of coordinate x and x′ in the draft space (that is free from external to the beam forces) 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 calculated results for the focus position (H_{focus}) measured with respect to the top wall of the vacuum chamber, the radial (σ_o) and the angular (σ'_o) standard deviations and the emittance value are presented in Table 1. The average of the emittance values is 0.2511.

Conclusions

The beam emittance as well as the electron beam density distribution are significant and appropriate characteristics of the beam quality. The measurement of these characteristics will: (i) help standardization of 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 the concrete welding technology from one welding machine to another and (iv) at creating expert systems for an operator choice of suitable regimes for gaining desirable welds.

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