Analysis of the secondary emission current and X-ray radiation dependency on the beam’s position along the joint during electron beam welding

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Abstract. We analyzed secondary emission current and X-Ray radiation dependency on the beam’s position along the joint during Electron Beam Welding of similar and dissimilar materials. We established that those characteristics were identical if the welding rim melting was absent. The characteristics are of extreme nature. During the welding of similar materials, the dependency minimum corresponds with the precise alignment of the beam’s position and the joint. During the welding of dissimilar materials, the minimum of the secondary emission current shifts towards the material with the lowest coefficient of the secondary emission and the minimum of the X-ray radiation shifts towards the material with the lowest atom number. The similarity of the characteristics is explained by the fact that the appearance of the secondary emission and the X-ray radiation is the result of the electron beam’s interaction with the material of the welded parts. Therefore, we can use the same mathematical tool to analyze the dependencies and joint tracking devices can be designed with unified hardware and software applications.

1. Introduction
Precise positioning of the beam along the joint of the welded parts is especially important when dealing with long joints during the welding of large parts. Acceptable error in positioning the beam with the joint usually does not exceed 0.2 mm. This precision requires the use of devices with automatic beam guidance along the joint.

Breaking X-ray radiation and secondary electron emission accompanying the Electron Beam Welding Process can be used as a source of information regarding beam’s position at the joint [1-3]. Figure 1 provides schematic for a receipt of secondary and X-ray radiation [4]. Figure 2 provides examples for positioning of the secondary electron sensor (figure 1, a) and the X-ray radiation sensor (figure 1, b).

The current of secondary electrons $I_{se}$ can be presented as follows: [5]:

$$I_{se} = \varphi I_b k_{se} k_{cse}$$  \hspace{1cm} (1)

where $I_b$ – the beam’s current; $k_{se}$ – coefficient that accounts for the number of secondary electrons reaching the sensor; $\varphi$ – coefficient of the secondary emission of the welded materials; $k_{cse}$ – coefficient that accounts for the influence of structural members on the current $I_{se}$.

Intensity of the X-ray radiation $J$ is determined by the following equation [6]:

$$J = CZU^2 I_b k_{XR} k_{cXR}$$  \hspace{1cm} (2)

where $C$ – proportionality coefficient ($C \approx 10^{-9}, \text{V}^{-1}$); $k_{XR}$ – coefficient that accounts for the share of
radiation reaching the surface of the sensor; $k_{cXR}$ – coefficient that accounts for the influence of structural members on the intensity $J$; $U$ – accelerating voltage; $Z$ – atom number of the welded materials.

Equations (1) and (2) show, that $I_{se}$ and $J$ with coefficient precision are determined by the beam current $I_b$. Once can assume that $I_{se}$ and $J$ depend on the beam’s position along the joint and these dependencies are of a similar nature. Thus, one mathematical device can be used to study these dependencies.

2. Formulation of the objective. Current density in the electron beam is not the same in its cross section and has probabilistic nature. Therefore, the beam current $I_b$ is expressed through the function of electron distribution along corresponding axes [7], and equations (1) and (2) can be presented as

$$I_{se} = k_{se} I_b \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} k_{cse}(x,y) \phi(x,y) j(x,y) \, dx \, dy,$$

$$J = C k_{XR} U^2 I_b \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} k_{cXR}(x,y) Z(x,y) j(x,y) \, dx \, dy,$$

where $j(x,y)$ – distribution density of electrons.

Density $j(x,y)$ is presented with a normal law of distribution [8]:

$$j(x,y) = \frac{1}{\sigma_x \sqrt{2\pi}} \exp\left[-\frac{(x-e_x)^2}{2\sigma_x^2}\right] \frac{1}{\sigma_y \sqrt{2\pi}} \exp\left[-\frac{(y-e_y)^2}{2\sigma_y^2}\right],$$
where \( \sigma_x, \sigma_y \) – standard deviation of electrons from the bunch axis along the corresponding axes; \( e_x, e_y \) – mathematical expectation – the beam’s axis position in coordinates (figure 3).

\[
\begin{align*}
\sigma_x, \sigma_y = \text{standard deviation of electrons from the bunch axis along the corresponding axes; } \\
e_x, e_y = \text{mathematical expectation – the beam’s axis position in coordinates (figure 3).}
\end{align*}
\]

The surface of the welded parts within the heating spot is considered homogeneous in along axis \( OY \). Then \( I_{se} \) and \( J \) do not depend on \( y \). Considering, that

\[
\frac{1}{\sigma_y \sqrt{2\pi}} \int_{-\infty}^{\infty} \exp \left[ -\frac{(y-e_y)^2}{2\sigma_y^2} \right] dy = 1,
\]

as integral from density of distribution in infinity limits, we can provide equations for \( I_{se} \) and \( J \):

\[
\begin{align*}
I_{se} &= \frac{k_{se}\lambda_b}{\sigma \sqrt{2\pi}} \int_{-\infty}^{\infty} k_{cse}(x) \varphi(x) \exp \left[ -\frac{(x-e_x)^2}{2\sigma^2} \right] dx, \\
J &= \frac{CK_{XR}U^2\lambda_b}{\sigma \sqrt{2\pi}} \int_{-\infty}^{\infty} k_{cXR}(x) Z(x) \exp \left[ -\frac{(x-e_x)^2}{2\sigma^2} \right] dx,
\end{align*}
\]

where \( \sigma = \sigma_x, \varphi = e_x \).

Comparison of these equations demonstrates dependencies of the X-ray radiation intensity and the secondary emission current from the beam’s position along the joint. The dependency is of a similar (extreme) nature. This provides an opportunity to use the same mathematical device to analyze the characteristics and application of well-known extremum seeking methods for achieving beam position control.

**3. Specific Cases.** During the Electron Beam Welding of parts shown on figure 3, there are no structural members interfering with the ability of the secondary electrons and the X-ray radiation to reach the corresponding sensors. In this case, \( k_{cse} = 1 \) and \( k_{cXR} = 1 \). Then

\[
\begin{align*}
I_{se} &= \frac{k_{se}\lambda_b}{\sigma \sqrt{2\pi}} \int_{-\infty}^{\infty} \varphi(x) \exp \left[ -\frac{(x-e_x)^2}{2\sigma^2} \right] dx, \\
J &= \frac{CK_{XR}U^2\lambda_b}{\sigma \sqrt{2\pi}} \int_{-\infty}^{\infty} Z(x) \exp \left[ -\frac{(x-e_x)^2}{2\sigma^2} \right] dx.
\end{align*}
\]

If welding similar materials, then \( \varphi \) and \( Z \) do not depend on \( x \) and the equations become:
where \( \Delta \) - gap in the joint (figure 3).

Figure 4 shows dependency \( I_{se} \) и \( J \) (in relative units) on the movement \( \varepsilon \) of the beam along the joint during the Electron Beam Welding of similar materials. To calculate absolute values, it is sufficient to multiply coordinates of both functions by the corresponding coefficients:

\[
I_{se} = k_{se} \phi F, \quad J = Ck_{XR} U^2 I_b Z F,
\]

where

\[
F = 1 - \frac{1}{\sigma \sqrt{2\pi}} \int_{-\Delta/2}^{\Delta/2} \exp \left( -\frac{(x-\varepsilon)^2}{2\sigma^2} \right) dx.
\]

Relative change of \( I_{se} \) и \( J \) with the constant gap in the joint grows with the decreasing \( \sigma \) (figure 4 b). This can be used along with a criterion of the electron beam focusing degree.

During the Electron Beam Welding of dissimilar materials, dependency of \( \phi(x) \) on \( Z(x) \) needs to be taken into account. For example, during the welding of copper (\( Z_{Cu}=29 \)) with steel (\( Z_{Fe}=26 \)), the equation for \( J \) in relative units is as follows:

\[
J = \frac{Z_{Cu}}{\sigma \sqrt{2\pi}} \int_{-\infty}^{-\Delta/2} \exp \left( -\frac{(x-\varepsilon)^2}{2\sigma^2} \right) dx + \frac{Z_{Fe}}{\sigma \sqrt{2\pi}} \int_{\Delta/2}^{\infty} \exp \left( -\frac{(x-\varepsilon)^2}{2\sigma^2} \right) dx.
\]

**Figure 4.** Calculation of dependency \( I_{se} \) и \( J \) on the beam position along the joint during electron beam welding of similar materials:

a) - \( \sigma = \text{const} = 0.1 \text{ mm} \), \( \Delta = \text{var} \): 1 - \( \Delta = 0.01 \text{ mm} \); 2 - \( \Delta = 0.05 \text{ mm} \); 3 - \( \Delta = 0.1 \text{ mm} \); 4 - \( \Delta = 0.3 \text{ mm} \);

b) - \( \Delta = \text{const} = 0.1 \text{ mm} \), \( \sigma = \text{var} \): 1 - \( \sigma = 0.35 \text{ mm} \); 2 - \( \sigma = 0.25 \text{ mm} \); 3 - \( \sigma = 0.15 \text{ mm} \); 4 - \( \sigma = 0.05 \text{ mm} \).

**Figure 5 a** provides calculated values according to last equation. **Figure 5 b** shows dependency \( J/Z_{Cu} \).
Figure 5. Dependency of $J$ on the beam’s position at the joint during electron beam welding of dissimilar materials.

Both graphs show that during electron beam welding of dissimilar materials slope angles for each characteristic are different. The metal with a higher atom number has a steeper angle (X-ray radiation intensity is proportionate with the atom number). Due to the same reason, the values of intensity saturation when the beam is fully positioned on one of the welded parts vary by a value that depends on the material atom number. In relative units, these values for $Cu$ and $Fe$ are equal to their atom numbers – 29 and 26, respectively (figure 5 a).

Another distinctive nature of these characteristics is that the extremum moves towards the material with the lower atom number. This is related to the fact that extremum coordinates are determined by the radiation parity from corresponding surfaces, which is proportionate to the electron bunch current and, therefore, to the area of the spot segment on the given metal. Since, $Z_{Cu} > Z_{Fe}$, for the above parity to happen, it is necessary for the spot area on the steel part to be bigger than the spot area on the copper part. Because of this, the beam is shifted towards the steel part.

Therefore, the joint position does not align with the position of the characteristic extremum, which needs to be taken into account during the electron beam welding of dissimilar materials.

The nature of extremum shift at various $\Delta$ is provided in figure 6 (graphs are based on the last equation).

Figure 6. Value of $J(\varepsilon)$ at various $\Delta$: $\sigma = 0.1$ mm;
1 - $\Delta = 0.2$ mm; 2 - $\Delta = 0.15$ mm; 3 - $\Delta = 0.1$ mm;
4 - $\Delta = 0.075$ mm; 5 - $\Delta = 0.05$ mm.

It is clear that noticeable position misalignment of characteristic extremum and the joint occur when $\Delta/\sigma \leq 1$. This is the most common case from practical standpoint and confirms the need to account for this misalignment.
By differentiating the last equation by $\varepsilon$ and equating the derivative to zero, we can determine $\varepsilon_0$ – extremum abscissa and its dependency on the joint gap: $dJ/d\varepsilon=0$
Therefore,

$$\varepsilon_0 \approx 0.0011 \frac{\Delta}{\Delta}.$$ 

In other words, the extremum abscissa during the electron beam welding of dissimilar materials is related to the joint gap with the hyperbolic law (figure 7). When the gap is less than 0.01 mm, position misalignment of the extremum and the joint can be substantial and cause significant errors in beam positioning based on the position of the extremum of the considered dependencies.

![Figure 7. Dependence of extremum position on the joint gap.](image)

Analysis of the dependency of the secondary emission current on the beam’s position at the joint produces the same results.

4. **Functional schematic for the joint tracking device.** Extreme nature of the above described dependencies allows an opportunity to design devices that can track joints using an extremum seeking method. One of these methods is the synchronization signal detection. The method assumes that spectrum components are present in the sensor’s signal and carry the information about the beam’s position on the joint. These components appear, for example, when the joint is scanned with the beam. Mathematically, this can presented as follows:

$$\varepsilon = \varepsilon_0 + \varepsilon_m \sin \alpha,$$

where $\varepsilon_0$ – beam shift relative to joint; $\varepsilon_m$ – searching beam shifting amplitude; $\alpha = \omega t$; $\omega$ – frequency, $t$ – time. Then, expression $F$ becomes:

$$F = 1 - \frac{1}{\sigma \sqrt{2\pi}} \int_{-\Delta/2}^{\Delta/2} \exp \left[ -\frac{(x - \varepsilon_0 - \varepsilon_m \sin \alpha)^2}{2\sigma^2} \right] dx.$$ 

Having periodical component in parameter $\varepsilon$, sensor output signal can be presented with Fourier series. Let us analyze the dependence of $\varepsilon_0$ on component $b_1$ with frequency $\omega$. This component is defined as Fourier coefficient:

$$b_1(\varepsilon_0) = \frac{1}{\pi} \int_0^{2\pi} F \sin \alpha d\alpha.$$
Figure 8. Dependence of the amplitude of sinusoidal component of the sensor signal with frequency $\omega_0$ on beam’s position at the joint: $\sigma=0.1\text{mm}$; $\delta=0.1\text{mm}$; $\varepsilon_m=1\text{mm}$.

Figure 8 provides graphic representation of the function $b_1(\varepsilon_0)$ based on the above formula. It shows that, at the joint, $b_1(\varepsilon_0)$ is proportionate to the mismatch of the beam and joint positions and the sign determines the direction of the mismatch.

This fact provides an opportunity to use synchronous sensor signal detection to obtain information on the beam’s position at the joint.

Figure 9 provides functional schematic for the automatic joint tracking device. Generator CG helps joint scanning with the beam that has frequency $\omega$ and amplitude $\varepsilon_m$. At the same time, the generator CG creates voltage reference (multiplier $\sin\alpha$), which enters one of the synchronous detector (SD) inputs. A signal from the sensor S (the secondary electron sensor or X-ray sensor) enters the input CD. A signal forms at CD output, that is proportionate to the product of the input and reference signals:

$$[b_1(\varepsilon_0)\sin\alpha] = [b_1(\varepsilon_0)]/2 - [b_1(\varepsilon_0)\cos2\alpha]/2.$$  

The signal from at the synchronous detector output is the sum of the constant component and the variable with the frequency of $2\omega$. Filter F shunts the high-frequency component, and the constant
current signal proportionate to the beam deviation enters into the deviating system DS through the power amplifier PS. This helps correct the beam’s position.

It is clear that, the signal form and its changes, depending on the beam’s position at the joint, match the calculated characteristics.

Technical design of the device is not complicated. Collector of the secondary electrons is used as a secondary emission sensor. Scintillation sensor with electron or silicon photomultiplier can be used as an X-ray sensor.

5. Conclusions
1. The similarity of dependencies between the secondary emission current and the X-ray radiation on the beam’s position at the joint is explained by the fact that the secondary emission and the X-ray radiation is the result of the interaction between the primary electron bunch and the material of the welded parts.
2. During the Electron Beam Welding of dissimilar materials, the minimum of the secondary emission current shifts towards the material with the lowest coefficient of the secondary emission and the minimum of the X-ray radiation shifts towards the material with the lowest atom number.
3. To reduce beam-joint alignment errors during the Electron Beam Welding of dissimilar materials, it is necessary to transmit an additional signal directed at the deflection system and that signal should be proportionate to the extremum shift of the reviewed characteristics.

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