Dependency of the X-ray radiation on the welding channel placement relative to the joint during electron beam welding

V Braverman and V Bogdanov
Reshetnev Siberian State University of Science and Technology, 660037, Krasnoyarsk, Russia

E-mail: braverman-vladimir@rambler.ru

Abstract. We investigate analytical description of processes for changes in the breaking X-ray radiation due to the welding channel placement relative to the joint of the welded parts during the Electron Beam welding. We establish that dependency of the X-ray radiation on the welding channel placement relative to the joint is extreme. The determination of the beam placement during the Electron Beam welding of dissimilar materials practically does not require accounting for extremum offset of the characteristics relative to the joint. Mathematical models are used to derive a system for automatic seam tracking during the Electron Beam welding.

1. Introduction
Precise positioning of the beam relative to the joint of the welded parts is important especially during the Electron Beam Welding of long joints. Relationship between the breaking X-ray radiation and the beam’s seam position can be used for this purpose. Scintillation detectors with NaI basis, activated by thallium (Tl) can be utilized as radiation sensors. Converting scintillation into an electric signal is achieved with the help of photoelectronic and silicon photomultipliers (figure 1).

Figure 1. X-Ray Sensor.
Our research [1] analyzes mathematical models for the relationship between changing X-ray radiation and the beam’s position relative to the joint in the absence of melting. We show that the information about the beam’s position relative to the joint of the welded parts can be obtained in near proximity of the welding channel by a brief withdrawal of the beam from the channel, taking measurements and then returning the beam back into the welding zone. Understandably, the withdrawal time should be set to avoid noticeable changes in the welding pool. This approach leads to a systematic error for the determination of the beam’s position relative to the joint related to the leading position of the measuring beam. Moreover, this approach calls for additional commutative operations to provide for sufficient speed of the beam movement, which requires the use of additional equipment and leads to lower reliability. We examine a possibility of obtaining the required information directly from the welding channel.

2. Problem Statement
In the described scenario, the X-ray radiation is registered from the welding channel and it weakens on its way to the sensor as it goes through the layer of each welded part. The thickness of the layer is determined by the welding depth and the sensor’s position in relation to the welded parts (figure 2).

\[ J(\varepsilon) = \left[ e^{-\mu_1} \int_{-\frac{\Delta}{2}}^{\frac{\Delta}{2}} e^{-\frac{\mu_1 (x-\varepsilon)^2}{2\sigma^2}} dx + \int_{-\frac{\Delta}{2}}^{\frac{\Delta}{2}} e^{-\frac{\mu_2 (x-\varepsilon)^2}{2\sigma^2}} dx + e^{-\mu_1} e^{-\frac{\mu_2 (x-\varepsilon)^2}{2\sigma^2}} \right] \]

(1)

where \( \mu_1, \mu_2 \) – coefficients of the weakening of X-Ray radiation from the welded parts; \( l_1, l_2 \) – average distance covered by the X-Ray beams in the welded parts; \( \sigma \) – standard deviation of the electrons from the bunch axis; \( Z_1 \) and \( Z_2 \) – atom numbers of the welded parts; \( \Delta \) – gap in the seam.

Figure 3 demonstrates the dependency of the X-Ray radiation intensity on the beam’s position \( \varepsilon \) relative to the seam of the AMg-6 alloy parts, calculated in accordance with the equation (1) with the equal thickness of the welded parts. Here \( l_1 = l_2 \). The dependency is extreme, but the characteristics of the extremum is maximum, in contrast to those considered in reference [1].

Location of the extremum corresponds with the position of the beam not shifted off the seam. With a constant \( \sigma \) and an increase in the gap, the relative intensity change of the X-Ray radiation also increases while the beam is moving relative to the joint. In other words, the character of the radiation intensity change is the same as in the instance when edge melting is absent.
During Electron Beam welding of aluminum, alloys of excess edges significantly impact X-Ray radiation intensity with the welding depth of under 15 mm. This is due to a small difference of the radiation weakening in materials with varying welding depth, explained by excess $\varepsilon$ (figure 4).

![Figure 3](image1.png)

**Figure 3.** Dependency of the radiation intensity on the beam’s position relative to the seam: $\sigma = 0.1 mm; h = 25 mm$; 1- $\Delta = 0.01$; 2- $\Delta = 0.05$; 3- $\Delta = 0.1$; 4- $\Delta = 0.15$; 5- $\Delta = 0.2$; 6- $\Delta = 0.5 mm$; $h$ - welding depth.

![Figure 4](image2.png)

**Figure 4.** Types of Excess Edges: a)–inaccurate assembly; b)–welding of parts of different thickness; d–thickness of the welded parts; $h$–welding depth.

Intensity of the X-Ray radiation going through material layer $x$ in relative units is determined by equation [2]:

$$J = e^{-\mu x},$$

where $x$ – thickness of the material layer.

It follows that for the alloy $AMg-6$ ($\mu = 147 m^{-1}$) with thickness $x = 15 mm$, approximately 90% of the radiation is dissipated in the material. Therefore, with greater welding depth, its changes in wide extremums do not significantly impact the radiation intensity and the characteristics that determine the radiation intensity based on the beam’s position at the seam with extended edges.

Figure 5 shows dependency graphs for scenario a) (figure 4) calculated based on equation (1) with the following: $d = 11 mm; h_1 = 10 mm, \Delta = 0.1 mm$ and $U_o = 60 kV$ for the alloy $AMg-6$. The graph makes it clear that the increase in extension $\varepsilon$ (reduction in welding depth $h_2$), the level of radiation increases when the beam moves towards the part with a lower welding depth. At the same time, characteristics extremum shifts in the same direction and the right distribution tail becomes flatter, in...
other words, the sensor conversion factor goes down. However, compared to the scenario when the edges do not melt [1], these changes are substantially smaller and appear when the extensions are greater. This is clear from the graphs in figure 6, calculated based on equation (1) at various welding depths and the same edge extensions in all cases.

Figure 5. X-Ray Radiation Dependency on $\varepsilon$: $1-z = 0; 2-z = 2.5; 3-z = 4; 4-z = 5; 5-z = 6; 6-z = 7 \text{ mm}$.

Figure 6. X-Ray Radiation Dependency on $\varepsilon$ with varying $h$ and constant $z$: $a-h_1 = 10; b-h_1 = 15; c-h_1 = 20; d-h_1 = 30 \text{ mm}$; $1-z = 0; 2-z = 2.5; 3-z = 4; 4-z = 5; 5-z = 6; 6-z = 7; 7-z = 8 \text{ mm}$.

It is clear that different characteristic slopes and the extremum shift are well observed at welding depths of up to 15 mm. Greater depth of the excess edge melting within the set range has almost no influence on the X-Ray radiation intensity. This points to the fact that during the Electron Beam Welding with excess edges, it is preferred to use the proposed method for registering the X-Ray radiation to obtain the information needed.

A similar situation occurs during the Electron Beam Welding of dissimilar materials. Thus, during the Electron Beam Welding of copper and steel with the accelerating voltage of 60 kV, the factors of the linear weakening are at 4.005 mm$^{-1}$ and 2.574 mm$^{-1}$ respectively. Therefore, even at the welding
depths of 5 mm or more, weakening X-Ray radiation (approximately by a factor of $e^{20}$ and $e^{13}$) is about the same. Because of this, the difference in slopes of the characteristics for the dependency of the X-Ray radiation intensity on the beam’s position at the seam and the extremum shift from the seam’s axis are most pronounced at the welding depth of less than 1 mm. Figure 7 demonstrates those dependencies calculated based on equation (1) with the accelerating voltage of 60 kV, seam gap of $\Delta = 0.1$ mm and $\sigma = 0.1$ mm.

![Figure 7](image)

Figure 7. X-Ray Radiation Dependency on $\varepsilon$ during Electron Beam welding of steel and copper: 1-h = 5; 2-h = 1; 3-h = 0.5; 4-h = 0.4; 5-h = 0.3; 6-h = 0.2; 7-h = 0.1 mm.

Calculation results confirm that it is appropriate to use the proposed method to measure X-Ray radiation intensity to control the position of the welding channel relative to the seam of the welded parts, especially during the Electron Beam Welding of dissimilar metals and a possible edge extension.

The extreme nature of the analyzed dependencies indicates a possibility of using devices to control the electron beam’s position during the Electron Beam Welding with known methods of the extremum search.

3. Conclusions

1. Extreme nature of the dependency of the X-Ray radiation intensity on the welding channel location relative to the seam indicates an obvious possibility of utilizing a technical solution for extremum search by relying on known methods and, thus, achieving control over the electron beam’s position with the required precision.

2. Determination of the seam position during the Electron Beam Welding of dissimilar metals and joints with excess edges in a wide range of welding depths does not require to account for the shift in the extremum of the characteristics relative to the seam, especially during the Electron Beam Welding of dissimilar metals with small gaps (which is a very common occurrence).

3. Relative changes in the X-Ray radiation intensity during beam movements along the seam can be utilized as criteria for the measuring device sensitivity to the beam’s movements relative to the seam.

References

[1] Braverman V, Belozertsev V, Goryashin N and Lelekov A 2009 Publication by the Siberian State Aerospace University named after the Academician M.F. Reshetnev (Krasnoyarsk Russia) 2 pp 247-251

[2] Haradza F 1966 Proc. Leningrad, Energiya (Russia) p 568