Using bremsstrahlung X-Ray for positioning of the filler wire during electron beam surfacing

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Abstract. This work aims to assess the bremsstrahlung X-Ray signal from the processing zone obtained by the use of a solid wire during electron beam surfacing. Applications of the bremsstrahlung X-Ray signal in the control systems allow positioning of the filler wire. During the experiments, a scintillation detector based on monocryalline iodine cesium and silicone photomultiplier was used for registration of the X-Ray signal. Circle oscillations of the electron beam create the informative component. Synchronous storage method was applied for mathematical treatment of the recorded signal.

1. Introduction

Electron beam surfacing using a filler wire provides an interesting alternative to the powder-based processes due to their simplicity and comparatively high deposition rates. During electron beam surfacing by wire materials, the quality of the produced surface bead depends on numerous factors. One of the most important factors is the accuracy of the filler material feeding in processing zone. The diameter of the electron beam in the focusing point is a part of the millimetre. Therefore, without operational control of the filler wire positioning, additional techniques must be used to avoid the deflection of the filler wire from the electron beam. More often, defocusing of electron beam is applied. Wherein, the electron beam size in plane of its interaction with the filler material obtains size comparable with the wire section. It leads to the decrease of the process energy efficiency, to an increased allowance for mechanical treatment and heat input into the work-piece with all following consequences [1-4].

Control of the filler wire position can be done by a hermetic video camera with a lighting system [5]. This control improves the quality of welded layer and the accuracy of surfacing, thus decreasing the need for following machining. The disadvantages of this method are relatively high cost of the equipment and difficulty to use the resulting video image in an automatic control system.

Another method for controlling the position of the filler wire is the monitoring the reflected electrons [6]. In this case, the electron beam periodically scans the processing zone with a frequency not less than 5 times per second. However, the periodical scanning leads to an interruption of the
The process that decreases the quality of welded layer and requires difficult handling of electron beam deviation. Moreover, this method creates 2D image from the processing zone with the necessity for further mathematical treatment that requires relatively high computing power and reduces the operating speed of the system.

The aforementioned problems may be solved, if the bremsstrahlung X-Ray is used as a feedback control signal. However, the continuous oscillation of the electron beam is necessary for the formation of the additional informative component into the X-Ray specter.

2. Methodology and experimental investigation

Experimental investigation is performed using austenitic stainless steel samples. As a filler material, a wire of 308L Si with 0.8 mm diameter was selected. The surfacing was carried out on an electron beam welder with acceleration voltage 60 kV and 6 kW power. The oscillations of the electron beam were carried out along a circle trajectory. The distance from the electron gun to the sample was 100 mm.

The influence of the variation of four factors on the obtained signal was investigated: velocity of wire feeding – $V_f$; oscillation frequency of the electron beam – $f$; radius of the oscillation circle – $R$; wire deviation from the oscillation center - $\Delta L$. The velocity of the sample movement was 5 mm/s. The power of the electron beam was 0.75 kW. The focus of electron beam was placed on the sample surface. The variation limits of the factors variables are shown in table 1. In the observed cases of welding with the defined process parameter values and regions, the penetration depth results from 1.5 to 2 mm.

| Factor  | Lower limit | Upper limit |
|---------|-------------|-------------|
| $\Delta L$, [mm] | -1.4 | 1.4 |
| $f$, [Hz] | 600 | 1200 |
| $R$, [mm] | 0.4 | 0.8 |
| $V_f$, [mm/s] | 2 | 4 |

The relative level of the bremsstrahlung X-Ray from the processing zone was measured through informative-measurement system with multichannel analogue-digital interface during surfacing. The
scintillation detector based on monocrystalline iodine cesium and silicone photomultiplier was used as X-Ray sensor, as shown in figure 1. The sensor was placed at a distance of 80 mm from work-piece at an angle of 45 degrees to the electron beam axis.

At the same time, signals, proportional to the current in the deflection coils, were registered. Measurement results were recorded in a file (figure 2) for further treatment. During the experiments, the value of discretization frequency of analogue-digital converting was chosen equal to 400 kHz for every measurement channel. Some experiments were obtained with 2 MHz discretization frequency.

![Figure 2. Recording of X-Ray signal; 1 - current in deflection coil of X axle (Osc(t)); 2 – the X-Ray signal (Data(t)) (∆L=0.1 mm; f=600 Hz; R=0.4 mm; Vf=2 mm/s).](image)

The recorded signals were processed using MathCAD software. The reference signal \( g(t) \) for the realization of the synchronous storage treatment was produced from the signal in the deflection coils \( Osc(t) \) representing rectangular ripples with small pulse ratio, as shown in figure 3.

![Figure 3. Reference signal for electron beam oscillation; 1 – oscillogram of the current in the deflection coil of the X axis (Osc(t)); 2 – formed reference signal \( g(t+\tau) \); \( \tau \) – offset of the reference signal, (∆L=0.1 mm; f=600 Hz; R=0.4 mm; Vf=2 mm/s).](image)

The reference signal \( g(t+\tau) \) with time offset \( \tau \) (0<\( \tau \)<\( T \), where \( T \) is the period of current oscillation in deflection coil) was multiplied on the X-Ray signal \( Data(t) \) and then integrated by the time \( t \). The result of this processing is the function \( S(\tau) \) (1), which takes into account the change of the synchronous storage result by the offset of the reference signal, as shown in figure 4.

\[
S(\tau) = \int_{0}^{t_0} g(t + \tau) \cdot Data(t) \, dt
\]  

(1)

where \( t_0 \) is the selection time, which was 100 ms.
3. Research results

Regression model for the dependence of the relative lag value $\Delta t_0/T$ of the function $S(\tau)$ reflective current signal in deflection coils from the center of the electron beam oscillation was estimated. The only statistically significant dependence was obtained for the wire deviation from the oscillation center $\Delta L$ (the corresponding coefficient is significant). The constant coefficient is zero, which corresponds to the physical considerations. The correlation coefficient was 0.972, which demonstrates that the estimated function gives good approximation of the observed parameters. The reliability of this model was proved by statistical analysis: the calculated Fisher criterion was $F = 31.65$ and the hypothesis for testing the significance of the correlation coefficient had rejection probability was $10^{-12}$. It should be noted that this dependence is applicable while $R=0.4\ \text{mm}$ and $\Delta L < R$. As a result, the estimated function takes the following form:

$$\frac{\Delta t_0}{T} = 0.25\Delta L$$  \hspace{1cm} (2)

The dependence of relative lag value $\Delta t_0/T$ on the value of the filler wire deviation from center of electron beam oscillation $\Delta L$ using the estimated regression equation is shown in figure 5.

The sign and value of relative lag value $\Delta t_0/T$ of function $S(\tau)$ depends on the filler wire deviation from center of electron beam oscillation. The relative lag value $\Delta t_0/T$ decreases from positive values with positive deviation of filler wire to negative values with negative deviation of filler wire and takes value zero when the position of filler wire aligns with the center of the electron beam oscillation, as shown in figure 5.

In this way, the aforementioned informative parameter allows to identify the position of the filler wire relative to the electron beam without using additional low frequency scanning of processing zone during electron beam surfacing.

Figure 4. Processing result of the X-Ray signal by the synchronous storage method; 1 - oscillogram of the current in the deflection coil of the X axis ($Osc(t)$); 2 – the processing result ($S(\tau)$), ($\Delta L=0.1\ \text{mm}; f=600\ \text{Hz}; R=0.4\ \text{mm}; V_f=2\ \text{mm/s}$).

Figure 5. Dependence of relative lag value $\Delta t_0/T$ on the value of the filler wire deviation from the center of the electron beam oscillation $\Delta L$ ($f=600\ \text{Hz}; R=0.4\ \text{mm}; V_f=2\ \text{mm/s}$).
4. Conclusions
Continuous oscillations of the electron beam during electron beam surfacing by a solid wire create an informative component for the bremsstrahlung X-Ray signal from the processing zone. The mathematical treatment of this signal using synchronous storage method allows extracting the value of the filler wire deviation from the center of the electron beam oscillation. It was shown that the dependence of the processing result – the relative lag value $\Delta t_0/T$ of function $S(\tau)$ on the filler wire deviation $\Delta L$ can be approximated by a linear function. Applications of the bremsstrahlung X-Ray signal in the control systems allow positioning of the filler wire during electron beam surfacing.

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