EBW of aluminium alloys with application of electron beam oscillation

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EBW of aluminium alloys with application of electron beam oscillation

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Abstract. This article presents the investigation results of influence of electron beam oscillation on the formation of welded joints of aluminium alloys. It is shown that for EBW with longitudinal oscillation, at a certain frequency and amplitude of oscillation, a lifting force appears. It acts on the metal of welding pool and displaces it from the root of the weld. The maximum lifting effect of liquid metal corresponds to a frequency of 35 Hz at amplitude of 1 mm (for aluminium alloys 12 mm thick at a welding speed of 90 m/h). The detected effect can be used for EBW materials of large thickness with through penetration.

1. Introduction
A distinctive feature of electron-beam welding (EBW) is the production of narrow welds of "dagger" shape. The hydrodynamic processes taking place in penetration channel are extremely complicated. They determine the behavior of liquid phase in welding pool and thus have a decisive influence on weld’s formation. Non-laminar movements of liquid metal along the walls of vapor-dynamic channel lead to the fact that level of the bottom of welding pool changes with the frequency of metal’s arrival. Thus, during the process of welding with non-through penetration specific defects in the form of a "root saw" are formed. They have hydrodynamic nature of formation and are due to the peculiarities of metal transfer in the welding pool [1, 2].

The existing methods of eliminating root defects are associated with the formation of a fairly wide root of vapor-dynamic channel with a rounded bottom. For this, various techniques are used, including those based on scanning an electron beam with different trajectories [3, 4], pulsed dynamic action on a welding bath [5], using of high-speed systems for monitoring electron beam focusing regime [6], etc. In addition removable weld backings, in which fusion peaks are derived, are widely used [1].

Defects of such kind are absent in the process of welding with a through-penetration, however, there are conditions for outlet of liquid metal from the root under the action of gravity, which lead to concavity of the weld in its upper part and, as a consequence, to weakening of the weld section. The increase of welding speed [1, 7], the use of removable weld backings (with transition to a welding scheme without through penetration) or transition to a welding scheme by means of horizontal electron beam, including special techniques [8], can be applied to eliminate such defects. However, it is not always possible to apply these technological methods due to the design features of welded joints and special requirements to welded joints.

Applying the oscillating motion of electron beam with frequency, equal to natural oscillation of molten pool, makes it possible to control the motion of liquid metal from melting front to crystallization front.
The results of saw-tooth sweep of electron beam (figure 1) during the process of electron beam welding (EBW) for steels 60 and 120 mm thick are described in different works [3, 5]. In these works the possibility of eliminating root defects, as well as obtaining narrower welds in comparison with static beam welding, is also demonstrated. When we use oscillations of electron beam during the process of welding, special attention should be paid to the choice of oscillation type, its frequency and amplitude. It is noted in the works [3, 5] that in the case when electron beam is thrown off by means of impulse in the direction of the tail part of the welding pool, and then during the most part of oscillation period it moves to the front part of welding pool (figure 1), welds turn out to be narrower and deeper. However, the authors of these works do not consider in detail the reasons of appearance of such effect and do not pay sufficient attention to determination of optimal parameters of electron beam’s oscillation.

Figure 1. Saw-tooth form of current $i(t)$ in the deflecting coil: $T$ is oscillation period; $\tau_1$ is time of beam motion to tail part of welding pool; $\tau_2$ is time of beam motion to melting front.

The purpose of this work is to develop methods to improve the quality of welded joints in EBW with through penetration based on changing the hydrodynamic processes of liquid phase motion in the welding pool by using special oscillations of electron beam and determination of its optimal parameters.

2. Method of study
All experiments were carried out on plates of AMg3 alloy with a thickness $\delta = 12$ mm. The welding process was carried out by the use of automatic installation of electron beam welding AELTK 344-12 with accelerating voltage $U = 60$ kV.

Figure 2. Macro-section of welds made of AMg3 alloy with a thickness $\delta = 12$ mm without electron beam oscillation: (a) $I = 73$ mA, (b) $I = 80$ mA.
For preliminary determination of electron beam parameters EBW of plates with a stationary beam at a speed of 90 m/h was performed. In this case, stable through penetration was observed at a beam current \( I = 73 \, mA \) (figure 2 (a)). The use of beam’s oscillation can lead to decrease in penetration depth, so for guaranteed receiving of through penetration, the beam’s current was increased up to \( I = 80 \, mA \) (figure 2(b)). The average joint width \( B_{av} = F_w/\delta \) (\( F_w \) is weld area) was 1.9 and 2.0 mm, respectively. In both cases, concavity of weld in its upper part was about 1.2 mm and in the root metal sagging was formed.

During the process of electron-beam welding steam and gas channel with high vapor pressure was formed. Sequential movement of heat source from melting front to tail part of welding pool should facilitate directional transfer of metal from melting front to crystallization region, and in order to obtain a qualitative effect, movement in the opposite direction should occur instantly. Thus, beam movement and current in deflection system must have the form shown in figure 3(a). For comparing the effect of direction of beam’s movement on the formation of welded joints, beam sweep with electron beam moving towards melting front (figure 3 (b)) was also investigated.

![Figure 3](image)

**Figure 3.** The form of current \( i(t) \) in the deflecting coil and movement of electron beam \( x(t) \) when beam sweep is directed "towards the welding pool" (a) and "towards the melting front" (b); \( x \) is beam's position change.

Obviously, in order to effectively influence the hydrodynamics of the welding pool and intensify liquid phase movement in the direction to crystallization front, frequency of oscillation of electron beam \( f \) must be equal to or multiples of the frequency of transfer of liquid phase from melting front to molten pool tail, and oscillation amplitude should be on order of the length \( L \) of the welding pool.

A quantitative estimate of the length of the welding pool was obtained from the equation of limiting state of the process of heat propagation from a powerful fast-moving linear heat source [10]. Its calculated value was 2.5 mm. Choice of beam oscillation amplitude along the entire calculation value of welding pool length is not advisable, because this will lead to an excessive increasing of the actual length of welding pool and reverse liquid metal flow in the direction to melting front. Thus, in the first approximation, oscillation amplitude \( A_0 \) was chosen to be approximately half of the estimated welding pool length and was equal 1.0 mm.

Experimental studies were carried out with using such types of electron beam sweep as "saw-tooth towards the welding pool" type (WP) and "saw-tooth towards the melting front" type (MF) (figure 3). The oscillation frequency was selected experimentally in the range from 12.5 to 200 Hz. Parameters of EBW regime are as follows: accelerating voltage \( U = 60 \, kV \), beam current \( I = 80 \, mA \), welding speed \( v = 90 \, m/h \). Table 1 summarizes variable parameters of beam sweeps and estimated parameters of welds: average width of weld \( B_{av} \), weld reinforcement area at the top of the weld \( F_T \) and at the root of the weld \( F_R \).
Table 1. EBW regimes and parameters of welds

WP – oscillation type "saw-tooth towards the welding pool"
MF – oscillation type "saw-tooth towards the melting front"

| Number of weld | Number of figure | Oscillation type | f, Hz | Ao, mm | B_{av}, mm | F_T, mm^2 | F_R, mm^2 |
|----------------|------------------|------------------|-------|--------|------------|-----------|-----------|
| 1              | 2b               | -                | 0     | 0      | 2.00       | -3.51     | 3.75      |
| 2              | 4a               | WP               | 12.5  | 1      | 1.58       | 0.73      | 0.00      |
| 3              | 4b               | WP               | 17.5  | 1      | 1.67       | 1.55      | -8.13     |
| 4              | 6a               | WP               | 25    | 1      | 1.61       | 4.03      | -3.80     |
| 5              | 6b               | WP               | 35    | 1      | 1.13       | 5.69      | -3.31     |
| 6              | 7a               | WP               | 35    | 1.5    | 1.48       | 3.10      | -2.02     |
| 7              | 7b               | MF               | 35    | 1      | 1.61       | 3.16      | -0.28     |
| 8              | 7c               | WP               | 50    | 1      | 1.54       | 2.92      | -0.88     |
| 9              | 7d               | WP               | 70    | 1      | 1.29       | 3.20      | -1.02     |
| 10             | 8a               | WP               | 100   | 1      | 1.61       | 1.56      | 0.60      |
| 11             | 8b               | WP               | 150   | 1      | 1.56       | -0.65     | 2.60      |
| 12             | 8c               | WP               | 200   | 1      | 1.84       | -1.25     | 2.80      |

3. Results of the study

When using oscillation type "saw-tooth towards the welding pool" with a frequency \(f = 12.5\) Hz (weld No.2, figure 4 (a)), point penetration with a period of 2.15 mm is observed and zones of incomplete fusion are registered. When using oscillation type "saw-tooth towards the welding pool" with a frequency \(f = 17.5\) Hz (weld No. 3, figure 4 (b)), the formation of the weld is similar, but alternation of penetration points is 1.25 mm.

The appearance of this defect is due to the fact, that at given oscillation frequencies the beam speed caused by the oscillations (12.5 mm/s and 17.5 mm/s) is much less than the velocity of electron gun relative to the product (25 mm/s). Figure 5 shows the displacement of the heat source at the oscillation
frequency $f = 12.5 \text{ Hz}$. It is obvious that there is no exposure of the electron beam in 1-mm-long section.

![Graph showing beam's movement at oscillation frequency $f = 12.5 \text{Hz}$](image)

**Figure 5.** Beam’s movement at the oscillation frequency $f = 12.5 \text{Hz}$. $S$ - beam’s movement, $t$ – time.

At the oscillation frequency $f = 25 \text{ Hz}$, continuous penetration is observed, the metal of the welding pool being forced out from the root with the formation of weld reinforcement on the front surface, and the root concavity is formed (joint No. 4, figure 6 (a)). At the oscillation frequency $f = 35 \text{ Hz}$ weld reinforcement on the front surface reaches a maximum value, as does the size of the root concavity, whereas the width of the weld sharply decreases (weld No. 5, figure 6 (b)).

Increasing the oscillation amplitude up to 1.5 mm (weld No. 6, figure 7 (a)) leads to increasing of the weld width, while the volume of the metal, which was forced out on the top surface, decreases, as does the concavity in the root of the weld. This fact indicates decreasing of the effect due to the use of beam sweep with increasing amplitude.

When using the oscillation type "saw-tooth towards the melting front" with the same frequency of $35 \text{ Hz}$ and AP = 1.0 mm (weld No. 7, figure 7 (b)), the stability of weld’s formation decreases, and the spattering from welding pool increases. Volume of metal, which was forced out from welding pool onto the surface, was reduced, therefore this type of beam sweep was no longer explored.

![Macro-section and surface formation of welds No. 4 and No. 5](image)

**Figure 6.** Macro-section (1) and surface formation (2) of welds No. 4 (a) and No. 5 (b).
With a further increase of the oscillation frequency type "saw-tooth towards the welding pool" up to 50 Hz and 70 Hz (weld No. 8 and 9, figures 7 (b) and (d)), reinforcement of the weld on the top side becomes more uniform, while root concavity is retained. At the oscillation frequency $f = 100$ Hz uniform reinforcement weld without concavity is formed both at the top and at the root of the weld (weld No. 10, figure 8 (a)). Increasing the oscillation frequency up to 150 Hz and 200 Hz (welds No. 11, figure 8 (b) and No. 12, figure 8 (c)) leads to concavity of weld, therefore increasing of beam’s oscillation frequency is inexpedient.

Dependence of the weld reinforcement in the top $F_T$ and in the root $F_R$ of the weld on the oscillation frequency $f$ of the electron beam (for "saw-tooth toward the welding pool" type oscillation) is shown in figure 9. At the oscillation frequency of beam of about 35 Hz, the process of metal transfer is the most intense, in this case the formation of maximum weld reinforcement at the top with periodic wavy character is observed. This fact gives reason to suppose that frequency of 35 Hz is equal to or is closest to the frequency of metal transfer from melting front to welding pool. At the same time, macrosections show crystallization waves (figure 6, weld No. 5), which confirm the periodicity of metal’s transfer from the melting front of the welding pool.
Figure 9. Dependence of weld reinforcement in the top $F_T$ and in the root $F_R$ of the weld on electron beam oscillation frequency $f$ (for "saw-tooth toward the welding pool" type oscillation).

In the absence of beam sweep, concavity of the weld in its top part is observed, and increasing the oscillation frequency up to 17.5 Hz results in the formation of a partial through penetration. Stable through penetration is formed, starting from a frequency of 25 Hz. In this case as frequency increases, reinforcement in the upper part of the weld decreases and at the frequency of 100 Hz reinforcement is formed, both on the root side and at the upper part of the weld. Further increasing of frequency leads to concavity of weld in its upper part.

Thus, when using "saw-tooth toward the welding pool" type oscillation of the electron beam, there is additional lifting force acting on the metal of welding pool and displacing it from the weld root to the top of the weld. This force is maximal at an oscillation frequency of 35 Hz and decreases with increasing frequency. Moreover, the dependence of reinforcement and concavity areas on the oscillation frequency in the interval from 70 to 200 Hz has a small gradient and the formation of a qualitative welded joint with reinforcement at the top and at the root of the weld should occur at oscillations with frequencies from 90 to 110 Hz.

In the case of increasing the thickness of the welds, the permissible range of oscillation frequency will shift toward the natural frequency of the oscillation of the welding pool in the consequence of increasing the column of liquid metal and, correspondingly, of increasing the gravity acting on the molten metal of the welding pool.

The dependence of average weld width on the oscillation frequency (figure 10) indicates the presence of extrema at multiple frequencies (35, 70, 140 Hz), which additionally confirms the periodic nature of metal’s transfer from the melting front in the welding pool.
Figure 10. Dependence of average weld width $B_{av}$ on electron beam oscillation frequency $f$ (for "saw-tooth toward the welding pool" type oscillation).

4. Conclusions
It has been established that application of "saw-tooth toward the welding pool" type oscillation of electron beam affects the movement of molten metal in the welding pool, causing a lift force that displaces metal of welding pool to the top and prevents it from flowing from the root of the weld. For AMg3 alloy with a thickness of 12 mm, this force has an extremum at the oscillation frequency of 35 Hz.

However, depending on the thickness of welded joints, it is necessary to select a frequency, so that the resulting lifting force compensates for the gravity with subsequent formation of welds with reinforcement in the top and in the root of the weld.

For EBW of alloy AMg3 with a thickness of 12 mm (regime of welding: current $I = 80 mA$, welding speed $v = 90 m/h$), qualitative formation of the welded joint occurs when oscillations of electron beam ("saw-tooth toward welding pool" type oscillation) with a frequency in the range of 90 ... 110 Hz are used.

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