# FEATURES OF PRODUCING SOUND WELDS IN ELECTRON BEAM WELDING OF THICK HIGH-STRENGTH STEELS

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Features of formation and solidification of weld metal in electron beam welding of high-strength steels with deep penetration were investigated. Both the possibility of increasing the degree of structural inhomogeneity and prevention of appearance of specific defects in welding with electron beam oscillation are shown.

***Keywords:*** *electron beam welding, high-strength steels, large thicknesses, weld metal, initial structure, weld defects, X-shaped path*

Pearlitic class high-strength alloyed steels 34KhN1M, 38Kh2NM, 40KhN2MA are widely used in manufacture of critical products for heavy and transportation engineering (axles, shafts and other heavy-duty parts). However, their poor weldability at application of arc welding processes greatly limits the possibilities of welded product design.

At present EBW is becoming widely accepted. It allows not only producing welds with high values of weld height-to-width ratio, but also provides minimum dimensions of the HAZ and high level of mechanical characteristics of welded joints. Statistical and numerical simulation is applied for EBW mode prediction [1–3]. At the same time EBW has a number of disadvantages: formation of specific defects in the weld root, instability of penetration depth, complexity of reproduction of electron beam focusing mode.

This work is a study of the features of producing sound welds at EBW of thick high-strength steels.

At the first stage of investigations cylindrical samples of 38Kh2NM steel with 30 mm wall thickness were welded in EB installation with ELA 60/60 power unit at 12 kW power and 14 m/h speed.

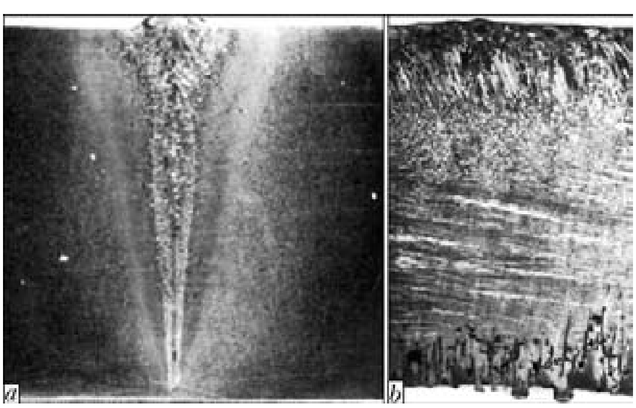

**Figure 1.** Macrostructure (×2) of weld metal in the transverse (*a*) and longitudinal (*b*) sections

Parameters of electron beam focusing were monitored and reproduced using a method developed by the authors, which is based on recording the high-frequency component of current of a non-self-maintained discharge in plasma. This discharge is excited in plasma, formed in the zone of application of high power density electron beam to the metal, through an electron collector located above the welding zone, and having a positive potential of 20–30 V relative to the product being welded [4, 5]. During experiments a component of 10–20 kHz frequency was singled out of the current spectrum of non-self-maintained discharge in plasma. Extreme values of this component amplitude were used to establish the «sharp» focusing of the electron beam providing the maximum depth of penetration at specified values of accelerating voltage and beam current.

Figure 1 shows macrosections of penetration zone obtained in welding by static electron beam. Macrosection clearly shows the keyhole penetration shape with a widened upper and narrowing middle and root parts of the weld, characteristic for welding mode with «sharp» focusing. The longitudinal section has specific root defects — peak formation and voids in the root part of the penetration zone.

Results of investigation of primary structure of weld metal established the presence of four characteristic zones, located along weld height, which are characterized by different dimensions and geometrical shape of primary crystallites (see Figure 1, *b*).

First zone (weld bead) consists of large polyhedral crystallites. Average diameter of crystallites, determined by the secant method, was equal to 0.25 mm in the cross section, and 0.32 mm in the longitudinal section, the depth of this zone being 1.5–2.0 mm.

The first and second structural zones form in the upper widened part of the weld. Macrostructure of these zones differs only slightly from the structure formed in arc welding processes.

The second zone consists of columnar crystallites directed normal to the fusion line in the weld cross-section, and practically vertically to its surface in the

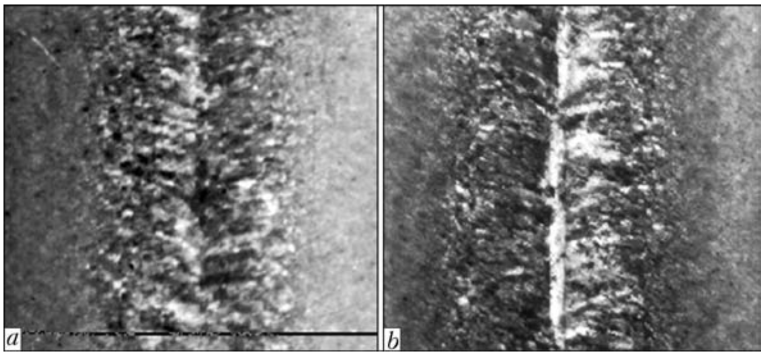

**Figure 2.** Nature of intergrowing of crystallites (×7) in the third (*a*) and fourth (*b*) zones

longitudinal direction. Average size of crystallites in the weld cross-section is equal to 0.9 × 0.3 mm, and in the longitudinal direction — 2.5 × 0.3 mm, second zone depth is 3.5–5.5 mm.

Third zone in weld cross-section consists of columnar crystallites, which intergrow in the weld center. Their axes are parallel to weld surface and normal to the fusion line. In the longitudinal section these crystallites have polyhedral structure (Figure 2, *a*). Average crystal diameter is equal to 0.15 mm, its length is about 0.66 mm, and angle of convergence of solidification fronts is minimum from both sides. Thus, intergrowing of crystallites in the weld center, reduction of their dimensions compared to crystallites of the first and second zones show that the solidification rate in this part of the weld is much higher. Increase of solidification rate is, certainly, related to more intensive heat removal, dependent on molten metal volume in different zones of the weld. Depth of the third zone is equal to 3.75–4.75 mm.

Difference of the fourth zone from the third zone consists in that in addition to columnar crystallites having the same orientation, in the central part of this zone fine polyhedral crystallites appear in the cross section (Figure 2, *b*). In the longitudinal section in the weld center these crystallites have columnar structure, being long and narrow with maximum length of up to 15 mm in the welding direction. Crystallite axes are practically parallel. In the fourth zone a considerable refinement of structure along the weld height was found. So, in the weld lower part in the cross-section crystallite length and width change from 0.97 to 0.27 and from 0.13 to 0.08 mm, respectively. In the longitudinal section crystallite length decreases from 15 to 1.6 mm, and their width changes from 0.41 to 0.12 mm along the weld center. Depth of this zone is equal to 12.5–15.0 mm. Thus, the given results are indicative of the fact that solidification rate increases with increase of zone depth.

Specific defects (peak formation and cavities) were found in welds, which form only in the fourth zone, and the largest of them — on the boundary of the third and fourth zone.

Investigations of weld metal showed that its structure is a finely-dispersed ferrite-carbide mixture with a fringe of proeutectoid ferrite along the dendrite boundaries. Primary structure along the weld zones is also greatly different. In the widened upper part of the weld the metal structure is of a pronounced dendritic nature with a rather wide ferrite net (Figure 3, *a*). In the weld middle its metal structure is cellular-dendritic, grain size decreases practically two times (Figure 3, *b*). A fine-grained structure forms in the weld root part, which is close to cellular structure by its type (Figure 3, *c*).

Measurements of grain size (width of dendrites and cells) by weld height showed that no significant refinement of dendrites was found in the first three zones. Average value of dendrite width in these zones is in the range of 21–24 μm. An abrupt refinement of the structure occurs along the fourth zone depth — from 6 to 20 μm.

On the whole it can be noted that in EBW by a static sharply focused electron beam, weld metal is characterized by a considerable structural and mechanical inhomogeneity. In addition, specific defects form in the weld root part, markedly lowering the welded joint service properties.

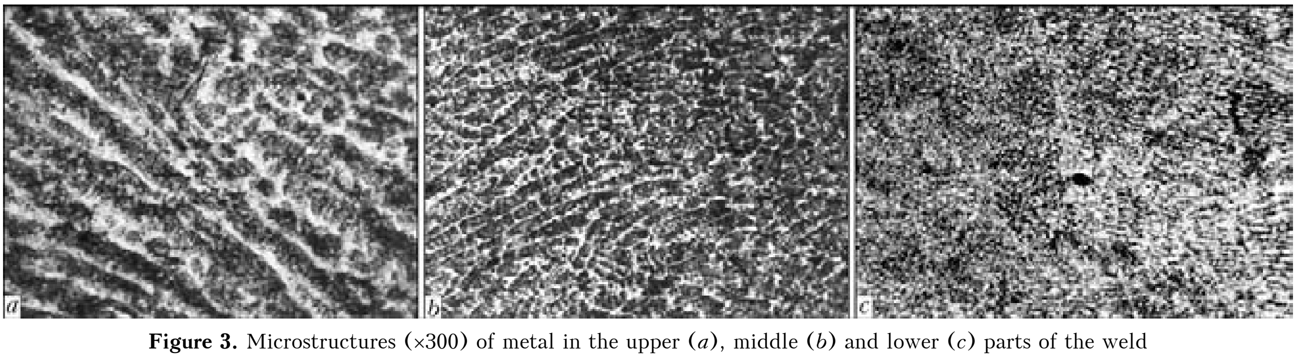

**Figure 3.** Microstructures (×300) of metal in the upper (*a*), middle (*b*) and lower (*c*) parts of the weld

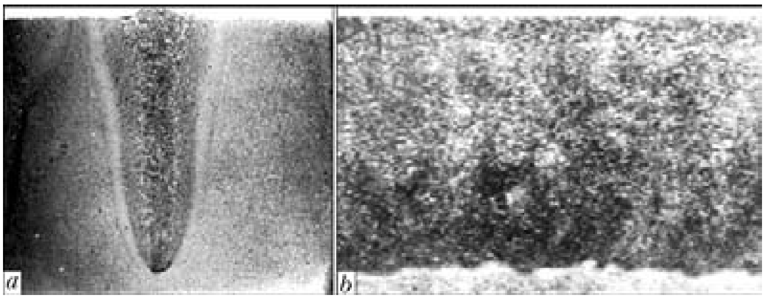


**Figure 4.** Macrostructures (×1) of weld produced in the transverse (*a*) and longitudinal (*b*) sections in EBW with X-shaped oscillations

The second stage included investigation of welded joint formation at EBW of 38Kh2NM steel with electron beam oscillation, which was performed in order to make a controlling impact on metal solidification processes and produce more sound welded joints. At selection of oscillation parameters (scanning frequency and amplitude) theoretical estimates proposed in [6] were used.

Studying welds made in welding with electron beam oscillation across and along the weld, as well as with electron beam rotation, showed that the above paths of electron beam scanning do not ensure any essential increase of structural homogeneity of weld metal, while absence of root defects is achieved only at large oscillation amplitude, leading to an essential lowering of penetration depth and increase of weld width.

Electron beam oscillation along the X-shaped path is of considerable interest in terms of formation of welds with a uniform structure and absence of root defects at optimum configuration of penetration zone [7]. In this connection formation of welds in EBW of 38Kh2NM steel with electron beam scanning along an X-shaped path was studied.

Welding was performed with mode parameters similar to those used in experiments on welding this steel by a static electron beam. Electron beam focusing, similar to experiments with a static beam, was optimized by parameters of high-frequency component of current of non-self-maintained discharge in the plasma formed in the beam impact zone.

Electron beam was scanned along the X-shaped path by changing phase shift $\varphi$ of harmonic beam oscillations in two planes normal to each other by the following law:

$$\Delta\varphi = \frac{\pi}{2}\left[1 - \mathrm{sign}\left(\sin\frac{1}{2}\,\omega t\right)\right],$$

where $\mathrm{sign}(U) = \begin{cases} 1 \text{ at } U \ge 0 \\ -1 \text{ at } U > 0 \end{cases}$; $\omega$ is the oscillation frequency; $t$ is the time.

Scanning frequency was selected in keeping with theoretical estimates taken from [6], and was equal to 600 Hz, and scanning amplitude, proceeding from the conditions of ensuring an optimum configuration of penetration zone with minimum increase of weld width, was 1.8 mm.

Investigation of macrostructure of a weld made at EBW with X-shaped oscillations showed an essential change of penetration zone configuration that is manifested in reduction of widening in the weld upper part, and formation of penetration zone of practically constant width. Penetration zone has the same characteristic zones, as in welding without electron beam oscillation, but here the level of penetration depth variation is markedly decreased, specific root defects are completely absent, and structure of the third and fourth zone changes (Figure 4). In the third zone the crystallites take an oval shape, which is almost polyhedral, and in the fourth zone the central section with polyhedral crystallites is increased. Columnar crystallites of this zone change their shape and become oval. Crystallite dimensions decrease along the entire weld length (Figure 4, *b*).

Thus, at EBW of high-strength steels an effective technique is electron beam oscillation along the X-shaped path at «sharp» focusing of the beam. In this case, production of weld metal with a high level of structural and mechanical homogeneity is ensured, and specific defects in weld root are absent.

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