WELDS FORMATION IN EBW OF HEAT-RESISTANT STEELS OF THE GRADES 10Kh9MFBA AND 10Kh12M

V.M. NESTERENKOV, L.A. KRAVCHUK, Yu.A. ARKHANGELSKY and **A.A. BONDAREV**
E.O. Paton Electric Welding Institute, NASU
11 Bozhenko Str., 03680, Kiev, Ukraine. E-mail: office@paton.kiev.ua

The influence of both the conditions of electron beam welding of heat-resistant steels 10Kh12M and 10Kh9MFBA 30 mm thick without preheating and also the spatial arrangement of electron beam relatively to the part being welded on weld formation and tendency to crack formation was investigated. It was established that in EBW of the mentioned heat-resistant steels without preheating the elimination of cracks and elongated cavities is achieved at the speed of welding of not more than 3 mm/s. The reproducibility of quality welds and formation of narrow and deep welds with parallel walls of cast zone is possible by application of technological scanning of electron beam around the circle and elliptic trajectory, and also arrangement of electron beam focus at the level of 2/3 of the specimen thickness. In the development of EBW technology of heat-resistant steels the non-destructive method of ultrasonic testing can be recommended for application. 6 Ref., 1 Table, 6 Figures.

Keywords: *electron beam welding, heat-resistant steels, electron beam, welding scheme, energy input, welding speed, focusing, defects, middle cracks, face and reverse weld beads*

In manufacture of such critical assemblies in machine building as bodies of drums, steam lines, diaphragms, rotors, discs, turbine blades and other high-loaded parts the heat-resistant steels of martensite-ferrite class are widely applied. Relating to the category of steels with a limited weldability, they require obligatory preheating in arc welding as they are susceptible to partial hardening with formation of martensite structures and cracks, and postweld tempering. These steels obtain the optimal properties as a result of double heat treatment by normalization + tempering or hardening + tempering, and are usually supplied for welding after final heat treatment.

EBW, the thermal cycle of which is featured by high rates of heating and cooling due to low value of energy input and also metal short-time duration at high temperatures, begins to occupy strong positions in power machine building. As compared to the arc welding, in ESW the sizes of near-weld zone and HAZ are decreased and also development of structure changes and deformations is delayed, which allows improving the mechanical characteristics of welded joints. The use of vacuum in EBW perfectly protects the molten metal from interaction with environment, which facilitates the improvement of quality of welded joints.

In this work the influence of conditions of EBW of heat-resistant steels of the grades 10Kh12M and 10Kh9MFBA of thickness δ = = 30 mm without preheating and also spatial location of electron beam relatively to the part being welded on welds formation and their tendency to cracks formation was investigated. It should be noted that investigated steels (Table) were supplied for welding under different heat conditions to obtain moderate levels of strength of base metal:

- 10Kh9MFBA alloy was subjected to the procedure of normalization + tempering: at normalization the specimens were heated to 1040–1095 °C, then the holding for 72 min and air cooling were followed; in tempering the specimens were heated to 770±10 °C, then the holding for 72 min and air cooling were followed;
- 10Kh12M alloy was subjected to the procedure of hardening + tempering: in hardening the specimens were heated to 1050 °C with subsequent cooing in oil; in tempering the specimens were heated to 720 °C with subsequent air cooling.

The welding of specimens was performed in the installation UL-209M with the power unit ELA-60/30 composed of EB gun with metal cathode and short-focus optics with electron beam current I_b = 0–500 mA. The tendency to cracks formation was determined on 200 × × 100 mm size butt specimens of δ = 30 mm. The control of electrode beam focusing on the surface of specimen was carried out according to the sharpness of image on the monitor of RASTR monitoring system [1], and at the same time according to the brightness of illumination of cir-

Chemical compositions of investigated heat-resistant steels, wt.%*

Grade of steel	C	Si	Mn	Cr	Mo	V	Nb	Cu	Ni	Other
10Kh9MFBA	0.07–0.13	0.15–0.55	0.27–0.63	7.9–9.6	0.8–1.1	0.16–0.27	0.05–0.11	≤ 0.25	≤ 0.43	S ≤ 0.01 P ≤ 0.02
10Kh12M	0.10–0.15	≤ 0.50	≤0.60	11.5–13.0	0.3–0.6	–	–	≤ 0.30	0.30–0.60	S ≤ 0.03 P ≤ 0.03

*Additional investigations on spectral analysis revealed gases in 10Kh9MFBA alloy: $[O_2] \le 0.0037$, $[N_2] \le 0.0386$, $[H_2] \le 0.0009$; in 10Kh12M alloy: $[O_2] \le 0.0033$, $[N_2] \le 0.0310$, $[H_2] \le 0.0008$ wt.%.

cular beam scanning of d_{circ} = 5 mm with $I_b \cong$ ≅ 10 mA on the copper massive plate. The narrow deep welds with parallel walls of cast zone were produced by deepening of electron beam focus inside the specimen, and also beam scanning around the circle or ellipsis, which provided the $\le 5 \cdot 10^{-2}$ rad convergence angle of beam at the working distance from lower end of gun to the specimen l_{work} = 200–250 mm [2, 3]. The presence of defects of welded joint formation was detected by non-destructive method of ultrasonic testing and further metallographic examinations. To eliminate the residual magnetization, all the specimens of investigated heat-resistant steels were subjected to additional demagnetization on a special stand and supplied for welding with the magnetization level of not more than 0.5 Gs.

At first, to produce the guaranteed weld formation on the investigated heat-resistant steels of δ = 30 mm, the through penetrations along the solid metal according to the scheme in flat position (vertical electron beam) at movement of EB gun along the coordinates X–X or Y–Y were performed. As a result, during change of beam current I_b in a wide range, focusing current I_f and welding speed v_w the defect-free weld could not be formed as far as on the face bead the non-regular depressions and undercuts of weld and wavy non-regular sagging of weld metal on reverse bead were formed.

To eliminate the defects of weld formation at through penetration of specimens of δ = 30 mm according to the scheme in flat position, the technological backing 8 mm thick from material to b welded was applied. The I_b value was selected so that in welding process the single spot penetrations (peens) could be made. As the results of through penetrations showed, in welding with technological backing the face bead is formed regularly without depressions and undercuts on the both investigated steels.

Tendency of steels 10Kh12M and 10Kh9MFBA to cracks formation was investigated after a number of through penetrations on solid metal of δ = 30 mm made according to the scheme in flat position with technological backing at v_w = 3, 6, 9 and 12 mm/s. The mode of penetration of specimens for both investigated steels at each selected speed of weldiand was not changed. The focusing current was preset so that electron beam focus was positioned below the surface of specimen at the level of 2/3 of thickness of specimen; for this case the value of partial focusing of electron beam from the value of focusing current on the surface of specimen corresponds to $-\Delta I_f$ = 15 mA. At l_{work} = 200 mm the technological electron beam scanning around circle of f_r = 500 Hz frequency amounted to d_{circ} = = 1.5 mm.

Ultrasonic testing and metallographic examinations of welded joints on the specimens of δ = = 30 mm showed that steel 10Kh12M has no tendency to cracks formation at v_w = 3–6 mm/s; only at v_w = 9 and 12 mm/s the macrodefect in the form of a middle crack of about 3 mm length and 0.05 mm width was detected approximately at the half of penetration depth. As is seen from Figure 1, with increase in speed of welding the weld configuration is changed: the width of face bead decreases, transverse section from conical one is approaching the cylindrical one. The face bead is formed at all speeds with reinforcement, undercuts on the edges of weld are absent. The detected middle crack of the sizes mentioned above was detected using ultrasonic testing.

Unlike steel 10Kh12M, in EBW of specimens of steel 10Kh9MFBA of δ = 30 mm the quite different results on tendency to cracks formation according to the scheme in flat position with technological backing were obtained. As metallographic examinations of welded joints showed, the cracks are absent at v_w = 3 mm/s (Figure 2, *a*); at v_w = 6, 9 and 12 mm/s the defects as middle cracks are detected, propagating in vertical direction along the weld axis from reinforcement to the root (Figure 2, *b*–*d*). The geometric sizes of middle cracks in upper and root part of a weld are practically similar to the defects on steel 10Kh12M.

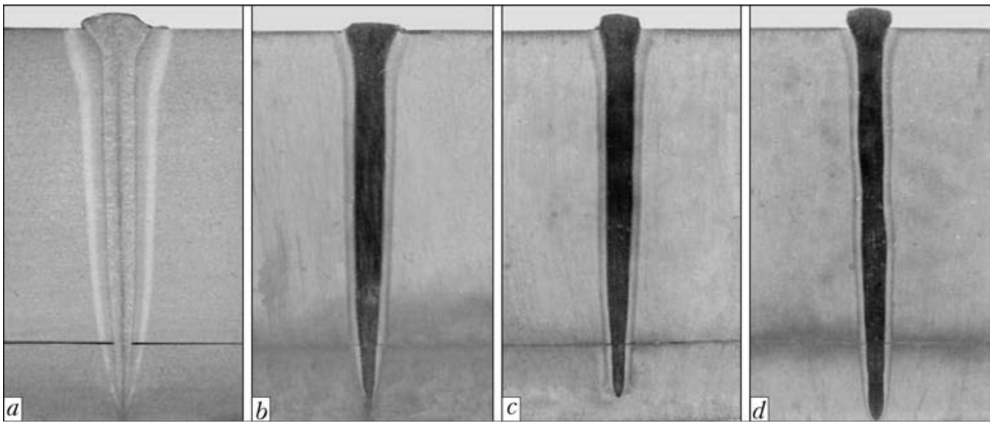

Figure 1. Macrostructure (×1.5) of welded joints on 10Kh12M alloy of δ = 30 mm in flat position at U_{acc} = 60 kV, I_f = = 630 mA, $-\Delta I_f$ = 15 mA, d_{circ} = 1.5 mm, l_{work} = 200 mm: *a* — v_w = 3 mm/s, I_b = 128 mA; *b* — v_w = 6 mm/s, I_b = = 184 mA; *c* — v_w = 9 mm/s, I_b = 236 mA; *d* — v_w = 12 mm/s, I_b = 310 mA

Thus, basing on the obtained results of through penetration of specimens of δ = 30 mm it can be concluded that with increase of welding speed the tendency to cracks formation on the investigated steels 10Kh9MFBA and 10Kh12M is increased, and this proves, in its turn, the fact that with increase of welding speed the increase of both welding stresses and also rate of growing of inner strains in welding occur. In other words, with increase of welding speed the quicker solidification of weld metal occurs, which leads to a higher rate of deformations growing [4, 5]. Therefore, the welding speed of not more than 3 mm/s can be more rational to be recommended for practical use of steels 10Kh12M and 10Kh9MFBA 30 mm thick in EBW.

According to the results of through penetrations of the specimens of heat-resistant steels 10Kh12M and 10Kh9MFBA 30 mm thick according to the scheme in flat position with technological backing (see Figures 1 and 2) the dependencies of energy input in EBW and width of face bead on the speed of welding were plotted. As is shown in Figure 3, with increase of welding speed in the range 3–12 mm/s the values of energy input q/v and width of face weld bead B are decreased in non-linear way according to hyperbolic law $(1/v_w)^{1/3}$: q/v = 2.56 kJ/mm and B = 5.8 mm at v_w = 3 mm/s up to q/v = = 1.55 kJ/mm and B = 3.5 mm at v_w = 12 mm/s, i.e. by 1.66 times. At v_w = 6 mm/s the value of energy input amounted to 1.84 kJ/mm and width of face weld bead B = 4.5 mm.

One can refuse from technological backings, having provided defect-free weld formation with through penetration, by transition to the scheme of EBW using horizontal electron beam and movement of EB gun in horizontal plane along the coordinate X–X or Y–Y. This method turned to be the most reliable and efficient, allowing elimination of root defects, reducing the angular deformations to minimum, decreasing the probability of pores formation and longitudinal cavities due to improvement of conditions of degassing of weld pool metal.

The first through penetrations of the specimens of steels 10Kh12M and 10Kh9MFBA of δ = = 30 mm using horizontal electron beam showed

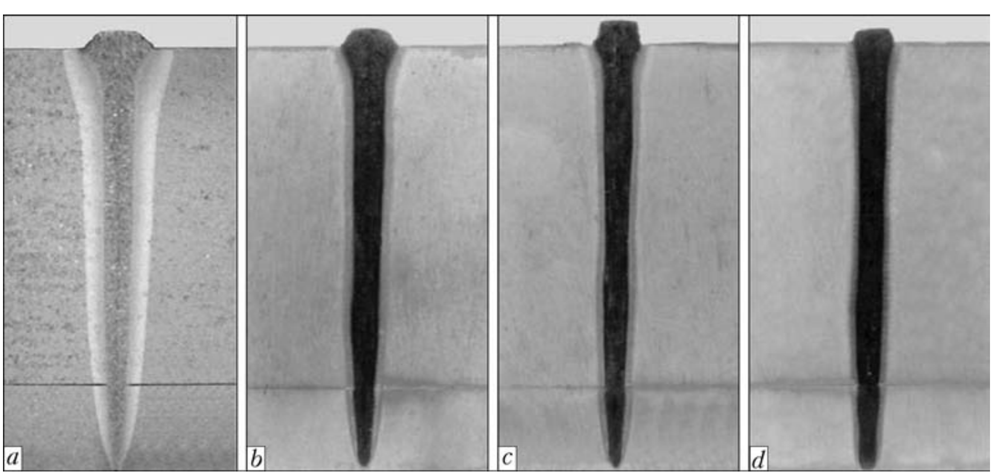

Figure 2. Macrostructure (×1.5) of welded joints on 10Kh9MFBA alloy of δ = 30 mm in flat position at U_{acc} = 60 kV, I_f = 630 mA, $-\Delta I_f$ = 15 mA, d_{circ} = 1.5 mm, l_{work} = 200 mm (*a*–*d* — v_w and I_b are the same as in Figure 1)

that direction of gravity force of liquid metal of weld pool has no considerable influence on selection of electron beam power, as compared to the similar welding conditions in flat position. In this connection and considering the recommendations [6], the through penetrations of specimens of investigated heat-resistant steels 30 mm thick with guaranteed face and reverse bead formation at different positions of electron beam focus relatively to the surface of specimen were carried out. As is shown in Figures 4 and 5, the face and reverse beads on the both steels are formed stably and regularly without depressions and flowing out of weld metal in the whole range of partial focusing $-\Delta I_f$ = 13–25 mA (electron beam focus is deepened inside the specimen), undercuts and visible defects are not observed. It should be noted that in welding of steel 10Kh12M the intensive spattering of weld metal from the face side occurs, unlike that of steel 10Kh9MFBA where EBW process is running much more smoothly.

According to the results of through penetrations of specimens of steels 10Kh12M and 10Kh9MFBA of δ = 30 mm using horizontal electron beam and basing on the analysis of transverse macrosections of welded joints given in Figures 4 and 5, the dependencies of width of face and reverse beads on deepening of electron beam focus inside the specimen at q/v = 1.98 kJ/mm were plotted. As is shown in Figure 6, the width of reverse weld bead b in the whole range $-\Delta I_f$ = = 13–25 mA remains practically constant and amounts to $b \cong 2$ mm, whereas width of face weld bead B with increase of deepening of electron beam focus inside the specimen is decreased in non-linear way: to $-\Delta I_f$ = 17 mA, where B is

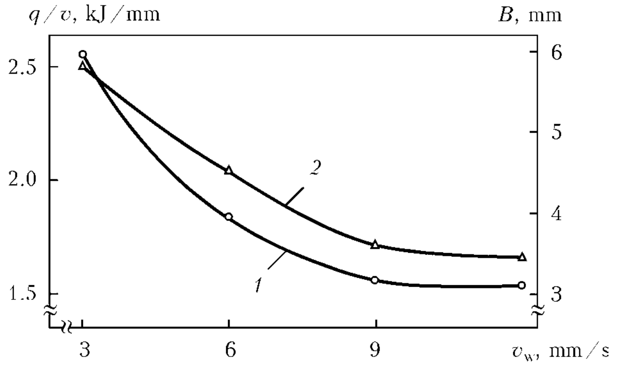

Figure 3. Dependence of energy input (*1*) and width of face weld bead (*2*) on speed of welding of steels 10Kh12M and 10Kh9MFBA of δ = 30 mm in flat position at U_{acc} = 60 kV, $-\Delta I_f$ = 15 mA, d_{circ} = 1.5 mm and l_{work} = 200 mm

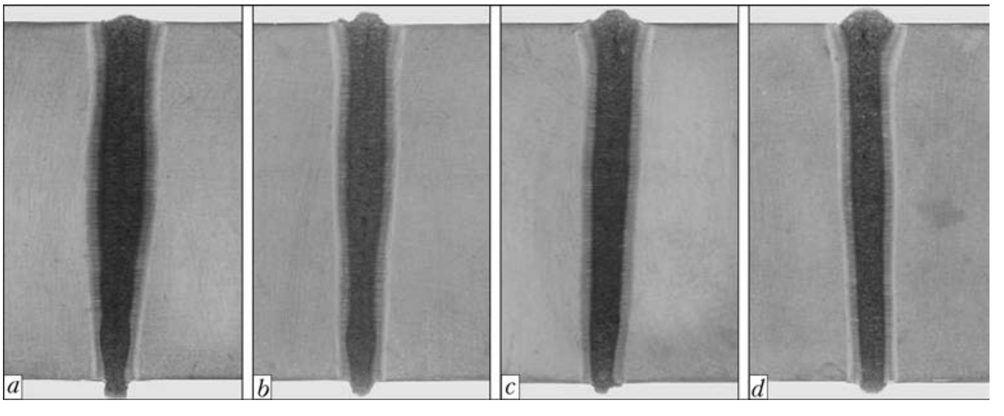

Figure 4. Macrostructure (×2) of welded joints on 10Kh12M alloy of δ = 30 mm in welding using horizontal beam at U_{acc} = 60 kV, I_b = 198 mA, v_w = 6 mm/s, d_{circ} = 1.5 mm and l_{work} = 200 mm: *a–d* — respectively, $-\Delta I_f$ = 25, 21, 17 and 13 mA

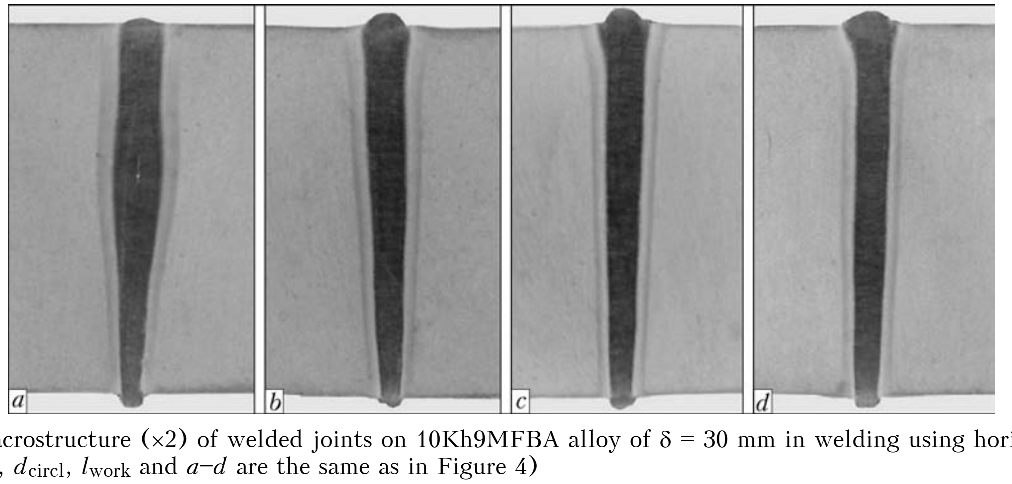

Figure 5. Macrostructure (×2) of welded joints on 10Kh9MFBA alloy of δ = 30 mm in welding using horizontal beam (U_{acc}, I_b, v_w, d_{circl}, l_{work} and *a–d* are the same as in Figure 4)

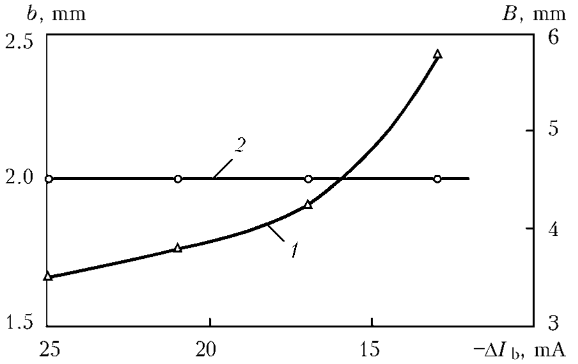

Figure 6. Dependence of width of face (*1*) and reverse (*2*) weld beads on deepening of electron beam focus in EBW of heat-resistant steels 10Kh12M and 10Kh9MFBA 30 mm thick using horizontal beam at U_{acc} = 60 kV, I_b = 198 mA, v_w = 6 mm/s, d_{circ} = 1.5 mm and l_{work} = 200 mm

sharply decreased, then to $-\Delta I_f$ = 25 mA, where the decrease of *B* parameter is delayed.

Metallographic examinations carried out on the welded joints of steels 10Kh12M and 10Kh9MFBA of δ = 30 mm after EBW using horizontal electron beam allowed establishing that position of electron beam focus relatively to the surface of specimen influences not only the shape of weld but also can result in cracks formation. As is shown in Figures 4, *a* and 5, *a*, at a large deepening of electron beam focus inside the specimen in the area of half of penetration depth on the both steels, the local widening of weld and middle cracks in them of up to 10 mm length are formed. With reduction of partial focusing current $-\Delta I_f$, local widening of weld is eliminated, and at $-\Delta I_f$ = 13–17 mA the weld shape from conical one is approaching the cylindrical one.

Conclusions

1. Welds formation with through penetration on heat-resistant steels 10Kh12M and 10Kh9MFBA of δ = 30 mm is achieved in transition to the scheme of EBW using horizontal electron beam and movement of EB gun in horizontal plane.

2. In EBW of these steels without preheating the elimination of cracks is achieved at the speed of welding of not more than 3 mm/s.

3. The application of technological scans of electron beam around the circular and elliptical trajectory and location of electron beam focus at the level of 2/3 of thickness of the specimen provides reproducibility of quality welds and also formation of narrow and deep welds with parallel walls of cast zone.

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Received 25.03.2013