METHODS OF GENERATION OF EXTERNAL MAGNETIC FIELDS FOR CONTROL OF ELECTROSLAG WELDING PROCESS

I.V. PROTOKOVILOV[1], **V.B. POROKHONKO**[1], **A.T. NAZARCHUK**[1],
Yu.P. IVOCHKIN[2] and **D.A. VINOGRADOV**[2]
[1]E.O. Paton Electric Welding Institute, NASU
11 Bozhenko Str., 03680, Kiev, Ukraine. E-mail: office@paton.kiev.ua
[2]Joint Institute for High Temperatures, RAS
13 Izhorskaya Str., Build. 2, 125412, Moscow, Russia. E-mail: vortex@iht.mpei.ac.ru

Efficiency of application of electromagnetic actions for control of joint formation during electroslag welding is determined in many respects by application of external magnetic fields to welding zone and structural peculiarities of corresponding devices. The aim of present work lied in analysis of methods for generation of external magnetic fields during electroslag welding of butt joints and evaluation of their effect on weld pool melt. The main methods of generation of longitudinal and transverse magnetic fields in a welding gap are considered, and principal schemes of corresponding electromagnetic devices are given. It is shown that direction and intensity of electromagnetic force effecting the weld pool melt is determined first of all by spatial orientation of the external magnetic field in relation to object being welded, value of field magnetic induction and its frequency characteristics. Rationality of application of that or another scheme of application of magnetic field in the gap depends on welded joint parameters, and it should be considered separately for each individual case. Appropriateness of application of magnetic fields providing constant (cyclic) rearrangement of hydrodynamic structure of flows in the weld pool or creating melt vibration was indicated. In this case, usage of pulsed magnetic fields generated by discharges of capacitor batteries to electromagnet coil is perspective. Relevance of development of new schemes and devices for generation of magnetic fields and their power sources is shown. 15 Ref., 9 Figures.

Keywords: *electroslag welding, weld pool, magnetic field, hydrodynamics, electromagnetic action, devices for magnetic field application, magnetic induction, electromagnetic force*

Electroslag welding (ESW) is one of the most efficient methods for joining of thick-walled parts and structures from different metals and alloys [1–3]. Scope of application and reasonable areas of ESW utilization could be more significant, if the joints performed by electroslag technology had relatively higher mechanical properties. Their low mechanical properties are caused by coarse, large-grain weld metal structure and unfavorable effect of welding thermal cycle on near-weld metal zone.

Control of weld pool hydrodynamics using external magnetic fields can provide effective improvement of service properties of the joints, performed by ESW. Positive effect of electromagnetic actions on welding process efficiency, refining of weld metal structure and mechanical properties of welded joints is marked in many works [4–12]. However, wide practical application of the obtained results is limited to significant extent by difficulty of receiving of external magnetic fields of necessary induction in the welding zone and inconvenience of corresponding devices.

The aim of present paper lies in the analysis of methods and structural schemes of application of external magnetic fields in the welding zone during ESW of butt joints, evaluation of their effect on weld pool melt considering the possibility of intensification of electromagnetic action.

Physical mechanism of the electromagnetic action during ESW lies in interaction of external magnetic filed with welding current passing in the melts of slag and metal pools [4]. A volume electromagnetic force $\vec{f_e}$ resulting in force action on the melt is formed due to such interaction in the weld pool. Value and direction of specified force is determined by vector product of current density in the melt $\vec{j}$ and induction of external magnetic field $\vec{B}$: $\vec{f_e} = \vec{j} \times \vec{B}$. It is sufficiently difficult to vary the value and direction of welding current in a wide range without deterioration of electroslag process stability and quality of welded joint formation. Therefore, efficiency of application of electromagnetic action is first of all determined by the parameters of external mag-

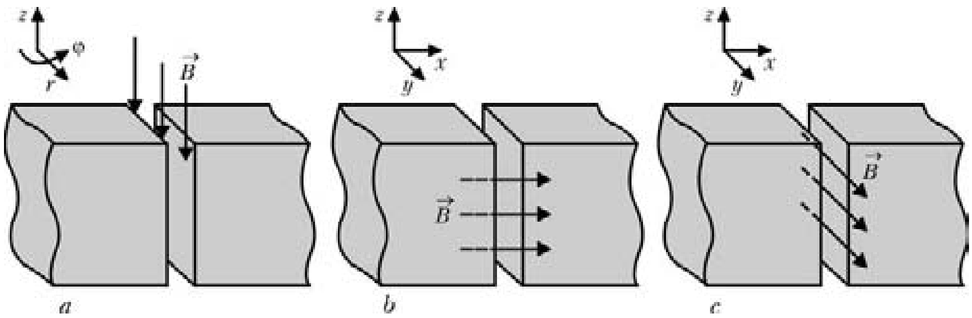


Figure 1. Variants of application of external magnetic fields to welding zone during ESW: *a* — longitudinal magnetic field; *b*, *c* — transverse magnetic fields

netic field, namely its spatial orientation in relation to object being welded, amplitude and frequency characteristics.

It should also be noted that the efficiency of application of magnetic fields in the welding zone is determined to significant extent by magnetic properties of parts being welded. More favorable conditions in most cases are developed during welding of nonmagnetic materials (titanium, aluminum etc.), since then the effect of shunting of magnetic field by surrounding ferromagnetic masses in the welding gap is minimal. An exception are the cases when the parts being welded or elements of fixture simultaneously perform functions of magnetic conductor.

Magnetic fields used in the welding processes are divided on longitudinal (along the electrode axis) and transverse (normal to electrode axis) ones [4, 5, 13, 14] (Figure 1) depending on the direction of induction vector. In turn, the force lines of the latter can be oriented normal to (Figure 1, *b*) or parallel (Figure 1, *c*) to edges being welded.

Longitudinal magnetic field under ESW conditions can be generated using a solenoid located in the welding gap in area of dry electrode extension [4, 6, 9] (Figure 2, *a*). Strictly speaking, the longitudinal magnetic field in this case is realized only in the middle part of the solenoid. The magnetic field having radial constituent in addition to axial one penetrates the weld pool. Thus, welding current will have $(j_r, j_z, 0)$ constituents, external magnetic field $(B_z, B_r, 0)$ and electromagnetic force $\vec{f}_e = \vec{j} \times \vec{B} = (0, 0, j_zB_r - j_rB_z)$ in the cylindrical coordinates (z, r, φ). It can be observed that the electromagnetic force generated by external magnetic field will result in melt movement in horizontal planes.

Studied scheme, providing local application of magnetic field in zone of melting of electrode wire, where the current density is maximum, allows effecting heat-and-mass transfer in given region and control formation and detachment of drops of electrode metal. However, only insignificant leakage field penetrates the metal pool that does not allow effecting the weld metal structure. Besides, present scheme of generation of magnetic field in the welding zone is poorly adaptable to fabrication and complex for practical realization in the most cases since the dimensions of magnetic system are limited by value of welding gap (25–35 mm). A scheme with magnetic conductor introduced in the welding zone and coil located outside (Figure 2, *b*) is considered to be more perspective.

Transverse magnetic field, the force lines of which are directed normal to the edges being welded (see Figure 1, *b*), can be realized with the help of windings covering the parts being welded and simultaneously performing functions of the magnetic conductor (Figure 3). The electromagnetic force will have the $\vec{f}_e = (0, j_zB_x - j_yB_x)$ constituents in Cartesian coordinate system (x, y, z). Since welding current constituent j_z significantly exceeds j_y constituent, then it can be considered that the main effect from action of indicated magnetic field lies in formation of the electromagnetic forces in the melt, oriented along the edges being welded (along *y* axis, see

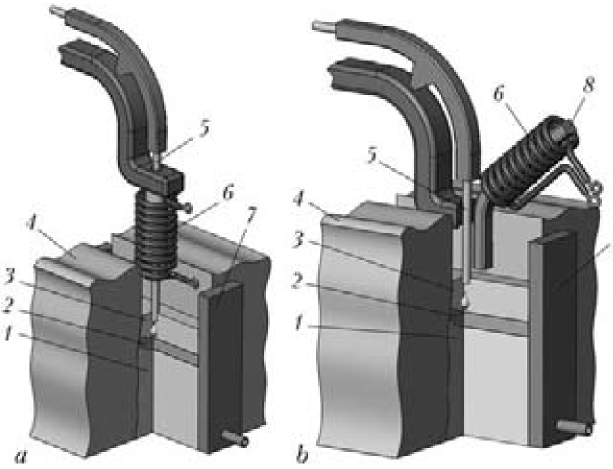


Figure 2. Schemes of application of longitudinal magnetic field by means of solenoid, positioned in welding zone (*a*), and bar magnetic conductor (*b*): *1* — weld; *2* — metal pool; *3* — slag pool; *4* — specimen being welded; *5* — wire; *6* — electromagnetic system; *7* — water-cooled forming strap; *8* — magnetic conductor

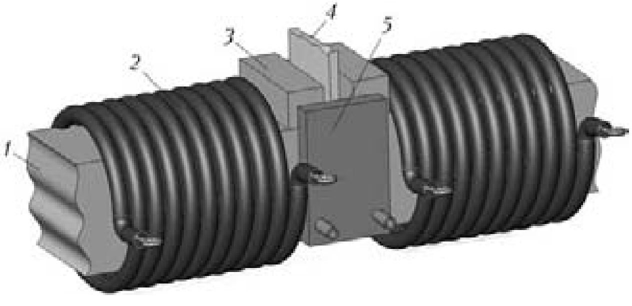


Figure 3. Scheme of application of transverse magnetic field with the help of coils mounted to welded parts: *1* — specimen being welded; *2* — electromagnetic system; *3* — tabs; *4* — electrode; *5* — water-cooled forming strap

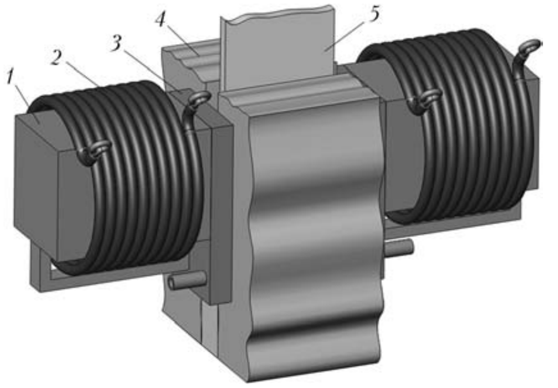


Figure 4. Scheme of application of transverse magnetic field with the help of electromagnets with bar magnetic conductor: *1* — bar magnetic conductor; *2* — coil; *3* — water-cooled forming strap; *4* — specimen being welded; *5* — electrode

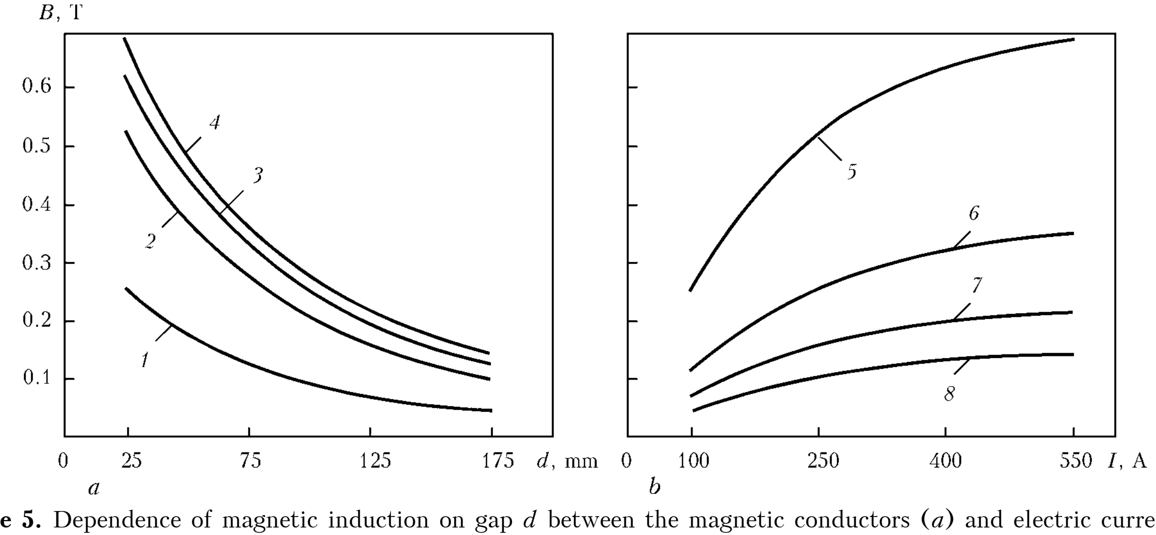
Figure 1, *b*). If external magnetic field is constant and welding current is alternating, then reciprocating motion (vibration) of the melt is created along the edges being welded with welding current frequency (50 Hz). Indicated effect can have positive influence on heat-and-mass transfer in the weld pool and refining of weld metal structure.

If welding current and magnetic field are alternating (or both constant), then presence of x and z constituents of electromagnetic force will result in complex volume pattern of the melt flow [4]. At that, z component of the electromagnetic force has opposite direction in two different parts of the pool, that leads to distortion of free surface of the slag pool. The latter is negative from point of view of welded joint formation since it violates process symmetry.

Advantage of given scheme of magnetic field generation lies in sufficiency of minimum gap between the magnets which is equal to welding one, that allows creating uniform magnetic filed with high induction values (up to 0.4 T). Such power magnetic fields allow influencing the macrostructure of weld metal refining and homogenizing it. It is, however, obvious, that given scheme is difficult to be realized in welding of large-size parts and parts with complex geometry. Therefore, it can find application only in welding of compact structures.

The most adaptable to fabrication and mostly applied scheme used in ESW (found in the literature) is the scheme of application of external transverse magnetic field with the help of electric magnets located near side forming devices [4, 5, 8, 12]. Welding of extended butt joints provides for their movement along the edges with welding speed. Electromagnet cores can be of bar as well as П-shaped forms.

Electromagnets with single-bar cores are sufficiently compact (Figure 4) [5]. Such devices mainly generate field, the force lines of which are normal to the edges being welded. In this case the electromagnetic force in Cartesian coordinate system (x, y, z) will have $\vec{f_e} = (-j_zB_y, 0, j_xB_x)$ constituents (see Figure 1, *c*), i.e. the main component of electromagnetic force will be directed across the edges being welded (along x axis) considering that $j_z > j_x$. This leads to vibration of the weld pool melt across edges being



a

b

Figure 5. Dependence of magnetic induction on gap d between the magnetic conductors (*a*) and electric current I in electromagnet winding (*b*): *1* — I = 100; *2* — 250; *3* — 400; *4* — 550 A; *5* — d = 25; *6* — 75; *7* — 125; *8* — 175 mm

welded, if constant magnetic field is used (welding current is alternating). Such reciprocating movements of the melt in double-phase area can promote fragmentation of growing crystalline particles and refining of weld metal structure. Transverse vibration in the welding gap also increases penetration of edges being welded that allows reducing rate of welding energy input [4, 10].

Disadvantage of given method of magnetic field application is its leakage due to significant gap between the electromagnet poles, which is determined by thickness of parts being welded and water-cooled forming starps (sliders). Increase of part thickness raises leakage and reduces efficiency of electromagnetic influence.

The results of experimental measurements of induction of magnetic field along the welding axis, generated by electromagnets with 70 cm^2 section of steel magnetic conductor and 160 total number of winds, are given in Figures 5 and 6. They show significant reduction of magnetic field induction at increase of gap between the magnetic conductors (thickness of parts being welded) (Figure 5, *a*) as well as relative inhomogeneity of distribution of magnetic induction in the welding gap (Figure 6).

Combined scheme of magnetic field action to the weld pool can be developed using bar electromagnets. The main principle of scheme lies in application of additional bar electromagnet located in the lower part of butt weld (Figure 7). Combined magnetic field having transverse and longitudinal constituents will effect the weld pool at specified coil connection. Longitudinal and transverse magnetic fields can be alternatively used applying switching of winding connection. Specified scheme expands the possibility of control of weld pool hydrodynamics. It is, however, obvious that it is not applicable during performance of extended welds.

Usage of electromagnets with П-shape core also provides the possibility of application of longitudinal and transverse magnetic fields (Figure 8) in the welding zone.

Magnetic field including mainly axial constituent (Figure 8, *b*) is formed in the gap at orientation of electromagnets along the welding axis and back-to-back connection of winding. Coordinated connection of windings can generate transverse field, the force lines of which have opposite directions in different zones on gap height (Figure 8, *c*). This provides the possibility to influence the melts of slag and metal pools using opposite fields and generating, for example, their vibration in antiphase at corresponding location of the magnets relatively to the weld pool. Specified effect can be useful for activating the processes of heat-and-mass transfers in the pool and slag–metal interaction.

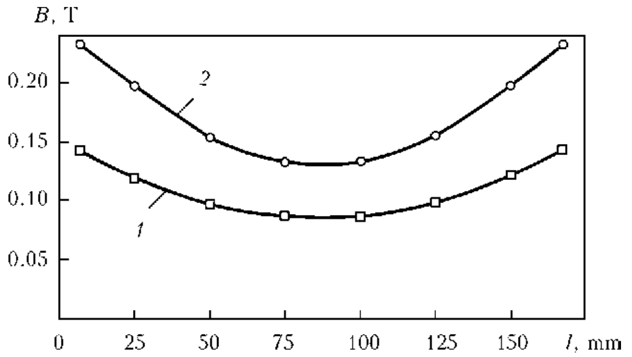


Figure 6. Distribution of magnetic induction in welding gap: *1* — *I* = 200; *2* — 400 A; *l* — distance from edge being welded

If electromagnets are located normal to the axis, magnetic field the force lines of which are directed from edge to edge, can be generated (Figure 8, *e*) in the welding zone.

Usage of considered above devices is complicated in series of cases by limited access to the parts being welded. Nonuniformity of magnetic field in the welding gap and necessity of movement of magnets along the edges during welding can be referred to their disadvantages.

Device for application of transverse magnetic field shown in Figure 9 [4] does not have specified disadvantages. The magnetic conductor of this device simultaneously performs the functions of sustaining walls for strap formed welds. Posi-

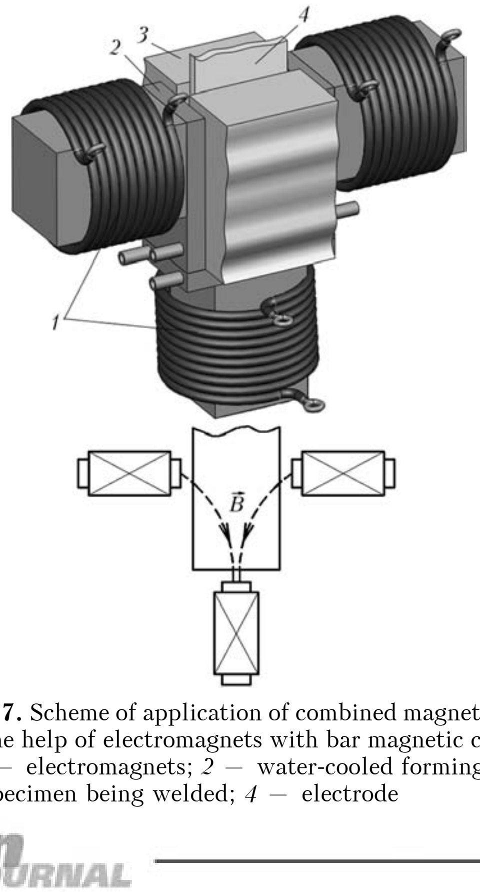


Figure 7. Scheme of application of combined magnetic field with the help of electromagnets with bar magnetic conductor: *1* — electromagnets; *2* — water-cooled forming strap; *3* — specimen being welded; *4* — electrode

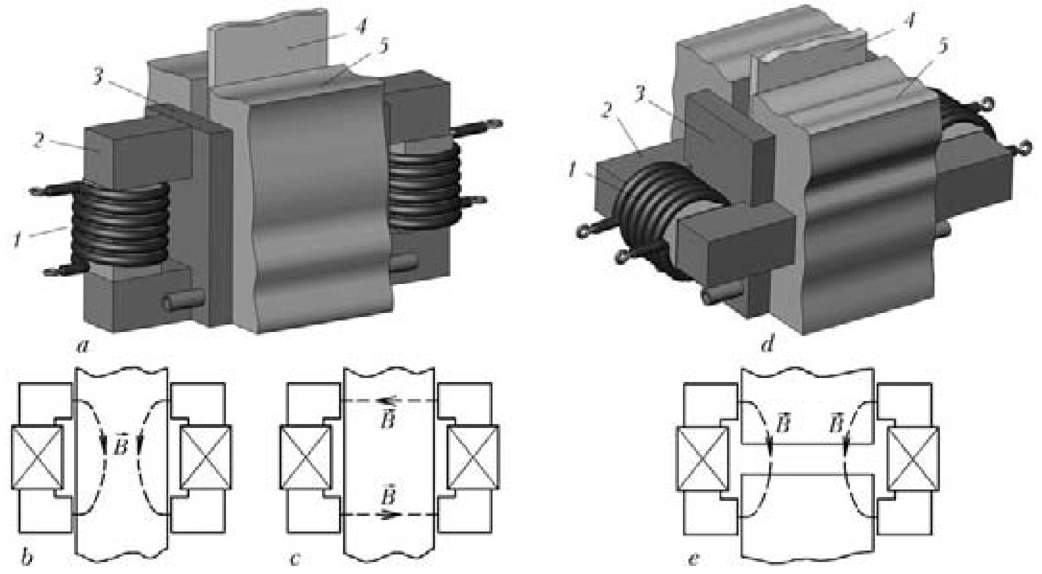


Figure 8. Scheme of application of transverse magnetic field with the help of electromagnets with П-shaped core, oriented along (*a*–*c*) and normal to (*d*, *e*) welding axis: *1* — coil; *2* — П-shaped core; *3* — water-cooled forming strap; *4* — electrode; *5* — specimen being welded

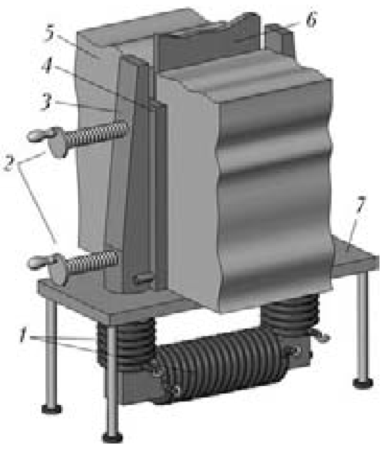


Figure 9. Device for electroslag welding in external magnetic field: *1* — coils; *2* — clamps; *3* — magnetic conductor; *4* — water-cooled forming strap; *5* — specimen being welded; *6* — electrode; *7* — support

tioning of magnet coils under the welding table in many respects facilitates operator work. The device allows generating the magnetic field along the whole weld length. Magnetic induction in the gap was calculated on formulae $\overline{B} = k\mu 0In/(l_{\mathrm{Fe}}/\mu_{\mathrm{Fe}} + d)$, where k is the coefficient considering leakage of field in the gap (0.75); $\mu_0 = 4\pi\cdot 10^{-7}$; I is the current intensity in windings; n is the quantity of winds; l_{Fe} is the length of magnetic conductor; μ_{Fe} is the magnetic permeability of magnetic conductor material; d is the gap between the poles.

Efficiency of electromagnetic action is determined by its frequency and amplitude characteristics except for spatial orientation of magnetic field.

Data given in the literature show sufficiently wide range of application of magnetic fields 0.01–0.20 T [4–12] used in ESW. Likely, that the relatively small induction values 0.01–0.05 T are enough for control of metal microstructure. However, experience of authors in application of control magnetic fields in electroslag processes shows that application of magnetic fields of higher power 0.1–0.2 T is necessary for influence the metal solidification and its macrostructure, control of weld pool parameters and penetration of base metal.

It should also be noted that action schemes, generating stable electrovortex flows in the pool, can have negative effect on chemical homogeneity and properties of deposited metal. Application of the fields providing constant (cyclic) rearrangement of hydrodynamic structure of flows or creating vibration of the pool melt is more efficient. Usage of pulsed magnetic fields, generated by discharges of capacitor batteries to electromagnet winding [15], is more perspective in this direction. Such scheme of action due to high peak currents in the windings (up to 10 kA) allows generating power magnetic fields in the welding zone when reducing of mass-and-dimension characteristics of corresponding devices.

Conclusion

Each scheme of generation of magnetic fields acting the ESW process, considered in the paper, has its advantages and disadvantages and relevance of application of that or another scheme should be considered separately for each specific case. Movable electromagnetic devices traveling along the weld together with forming sliders is good to use in performance of extended welds. Stationary electromagnets can be used in welding of compact sections.

Since generation of the magnetic field of sufficient induction (0.1–0.2 T) in the welding zone is difficult during ESW, then its application for influence the solidification of weld metal is less efficient than usage of the transverse magnetic fields. At that, application of pulsed fields providing constant (cyclic) rearrangement of structure of pool melt flows or developing its vibration at reduction of mass-and-dimension characteristics of corresponding devices is the most perspective one.

Further investigations in area of electromagnetic control of ESW process should be complex, i.e. by development of efficient schemes of generation of magnetic fields in the welding gap considering structural peculiarities of electromagnetic devices for their generation and designing of power sources for them.

The works are performed with the assistance of the State Fund for Fundamental Researchers of Ukraine (project No.F53.7/027) and Russian Foundation for Basic Research (project Ukr_f_a No.13-08-90444).

1. (1980) *Electroslag welding and surfacing*. Ed. by B.E. Paton. Moscow: Mashinostroenie.
2. Yushchenko, K.A., Lychko, I.I., Sushchuk-Slyusarenko, I.I. (1998) Effective techniques of electroslag welding and prospects for their application in welding production. In: *Welding and Surf. Rev.*, Vol. 12, Pt 2. Amsterdam: Harwood Acad. Publ.
3. Paton, B.E., Dudko, D.A., Palti, A.M. et al. (1999) Electroslag welding (prospects of development). *Avtomatich. Svarka*, **9**, 4–6.
4. Kompan, Ya.Yu., Shcherbinin, E.V. (1989) *Electroslag welding and melting with controllable MHD-processes*. Moscow: Mashinostroenie.
5. Kuznetsov, V.D., Kozakov, N.K., Shalda, L.M. (1987) *Magnetic control of electroslag process*. Kiev: Vyshcha Shkola.
6. Dudko, D.A., Rublevsky, I.N. (1960) Electromagnetic stirring of slag and metal pools in electroslag process. *Avtomatich. Svarka*, **9**, 12–16.
7. Trochun, I.P., Chernysh, V.P. (1965) Magnetic control of solidification in ESR. *Svarochn. Proizvodstvo*, **11**, 3–5.
8. Protokovilov, I.V., Porokhonko, V.B. (2012) Control of formation of welded joints in ESW (Review). *The Paton Welding J.*, **10**, 49–54.
9. Kompan, Ya.Yu., Petrov, A.N., Sharamkin, V.I. (1978) Some peculiarities of electroslag welding in longitudinal-radial magnetic fields. *Avtomatich. Svarka*, **9**, 39–43.
10. Porokhonko, V.B., Protokovilov, I.V., Petrov, D.A. (2012) Specifics of electroslag welding of titanium using electromagnetic methods effects. *Visnyk Adm. Makarov NUK*, **5**, 170–176. *http://*ev.nuos.edu.ua/ua
11. Volkov, G.G. (1975) Electroslag welding with application of alternative electromagnetic field. *Montazh i Spets. Raboty v Stroitelstve*, **8**, 14–15.
12. Kazakov, N.K., Kuznetsov, V.D., Korab, N.G. (1981) Selection of magnetic field input method during electroslag welding. *Vestnik KPI*. Series Machine Building, Issue 18, 76–78.
13. Ryzhov, R.N., Kuznetsov, V.D. (2006) External electromagnetic effects in the processes of arc welding and surfacing (Review). *The Paton Welding J.*, **10**, 29–35.
14. Razmyshlyaev, A.D., Mironova, M.V., Yarmonov, S.V. (2013) Transverse magnetic field input devices for arc welding and surfacing processes (Review). *Ibid.*, **1**, 39–43.
15. Kompan, Ya.Yu., Nazarchuk, A.T., Protokovilov, I.V. et al. (2012) Possibilities of application of pulse electromagnetic effects in electroslag processes. *Sovr. Elektrometallurgiya*, **2**, 8–13.

Received 15.08.2013