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DEVELOPMENT OF A NON-STATIONARY MATHEMATICAL MODEL OF PENETRATION ZONE FORMATION DURING ELECTRIC ARC SURFACING

RAZVOJ NESTACIONARNOG MATEMATIČKOG MODELA FORMIRANJA ZONE PENETRACIJE PRI ELEKTROLUČNOM NAVARIVANJU

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- penetration zone
- pressure balance
- mathematical model
- weld pool formation
- heat source

Ključne reči
- elektrolučno navarivanje
- zona penetracije
- ravnoteža pritiska
- matematički model
- formiranje zavarivačkog kupatila
- izvor toplote

Abstract

The article presents the development of a non-stationary mathematical model of penetration zone formation during electric arc surfacing. Simulation of the evolution of the penetration zone in time with a stationary heat source is carried out. The possibility of using penetration depth data obtained on a model of a fixed arc in the range of surfacing speeds is substantiated. In order to analyse the pressure balance in the case of a stationary heating source, a design scheme of the pressure balance in the weld pool is constructed.

It has been calculated and experimentally established that the increase in penetration depth occurs until the moment at which the arc pressure is balanced by the metal-static pressure of the molten metal in the weld pool. Based on this condition, a model of the weld pool formation in an unsteady mode is created.

Izvod

U radu je predstavljen razvoj nestacionarnog matematičkog modela formiranja zone penetracije pri elektrolučnom navarivanju. Izvedena je simulacija procesa razvoja zone penetracije tokom vremena sa stacionarnim izvorom toplote. Data je mogućnost primene podataka o dubini penetracije, dobijenih na modelu sa fiksnim lukom u oblasti brzina navarivanja. Za potrebe analize ravnoteže pritiska u slučaju stacionarnog izvora toplote, konstruisana je shema izvedbe za ravnotežu pritiska u zavarivačkom kupatilu.

Rezultati dobijeni proračunom i eksperimentima pokazuju da povećanje dubine penetracije nastaje u moomentu kada je pritisak električnog luka uravnotežen statičkim pritiskom rastopljenog metala u zavarivačkom kupatilu. Na bazi ovog uslova, razvijen je model formiranja zavarivačkog kupatila u nestacionarnim uslovima.

INTRODUCTION

The use of well-known mathematical models created on the basis of the theory of diffusion heat transfer, in many cases associated with welding technologies, overlaying and hardening /1-4/, does not allow obtaining sufficient convergence of simulation results with experimental data. This especially concerns the calculated data of the penetration depth for the case of a fixed weld pool, which takes place at the beginning of the formation of the deposited bead and during crater filling, as well as in other cases when the use of models describing a quasi-stationary state is not correct, for example, when surfacing layers in a complex relief /5/, as well as with variable composition and properties /6/.

Taking into account convective phenomena in the weld pool /7-10/ may significantly increase the accuracy of predicting its parameters, but, at the same time, leads to a complication of the computational technique, which contributes to increased time and computing power for modelling.

Insufficient convergence of results in terms of penetration depth for stationary models as well as the absence of mathematical models of heat distribution under non-stationary conditions requires the improvement of the theoretical basis and calculation methods, including the use of the penetration depth parameter as a function of time. Such an approach will improve the efficiency of electric arc surfacing and will provide an opportunity to use automated equipment for real-time process control.

The main attention is paid to modelling the evolution of the penetration zone in time with a stationary heat source, since the calculated data obtained for a fixed weld pool (v_s = 0 m/s) can be used for the case of arc motion with a welding speed, if we take into account that according to the data obtained for thick base metal /11/, when a three-dimensional heat removal scheme is implemented, 90% of the entire surfacing current I_s flows precisely in the head of the weld pool.

Since the weld pool metal in front of the arc has a lower temperature compared to other directions, the density of the current flowing through the liquid metal of the weld pool's end is at least an order of magnitude lower than in the main part of the weld pool. In this case, it is necessary to take into account the increase in penetration rate of the base metal due to the decrease in thickness of the liquid metal layer on the front wall of the pool crater under the arc and the change in force balance in the liquid associated with this factor.

If we depict the average dependence of penetration zone depth for wire electrodes in the range of diameters 3-5 mm vs. surfacing speed (Fig. 1) for conditional stationary (1), mobile (2), and fast-moving (3) heat sources, we can observe that in zone 2, the effect of surfacing speed is negligible.

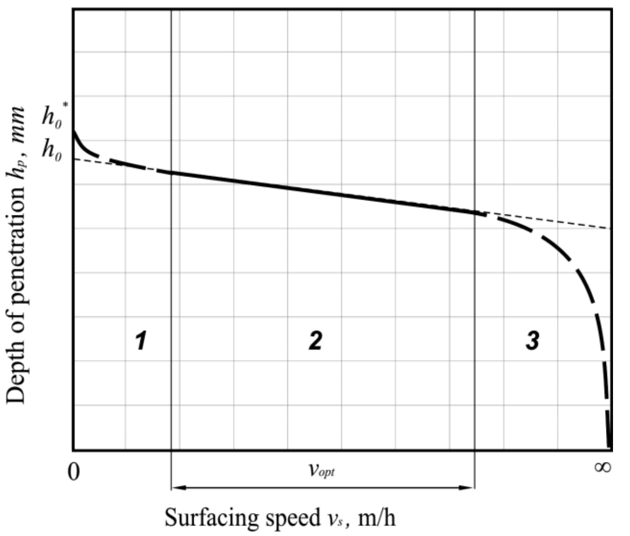

Figure 1. Dependence of averaged penetration zone depth on the deposition rate for wire electrodes of diameters 3-5 mm: 1, 2, 3 - deposition rate zones in which the dependence changes.

Hence, we can conclude that an increase of deposition rate within the main technological range does not lead to significant change in the balance of force factors in the weld pool, as well as the distribution of liquid metal velocities and temperatures in the penetration zone of the base metal.

In the region of small velocities (zone 1 in Fig. 1), if we rely on the principles of heat conduction theory, the penetration depth should increase depending on the inverse of zone 3, crossing the ordinate axis at the point of maximum penetration depth h_0^* for corresponding parameters of the surfacing mode (the approximate curve in Fig. 1 is indicated by a dashed line). However, during experimental surfacing for a stationary heat source, the maximum penetration depths are significantly below this value (point h_0 on the ordinate axis, Fig. 1). It should be noted that the value of penetration depth in section 1 with a decrease in surfacing speed to $5 \cdot 10^{-4}$ m/s practically does not increase, thus, increases only when approaching the zero value of speed, that is, when the heating source stops.

Thus, the obtained data allow us to make an assumption that in the range of surfacing speeds widely used in production $(1.4\text{-}11) \cdot 10^{-3}$ m/s, it is possible to use the penetration depth data obtained on the fixed arc model.

This circumstance is very important for determining the manufacturing sequence in both the model and calculating the size of the penetration zone based on it, both in the case of a stationary heating source and in the case when it moves with the surfacing speed in the considered range.

METHODS OF RESEARCH

Since the standard diffuse theory of heat distribution makes it possible to calculate with large approximation the size (shape) of a stationary weld pool by changing the distribution of the heat source and thermophysical constants for the base metal, taking into account only the diffusion component of heat transfer does not reflect the facts actually observed in the experiment. This circumstance requires the development of new approaches for solving the problem of determining the size of the penetration zone of the base metal during electric arc surfacing in an unsteady mode with a fixed arc ($v_s = 0$ m/s).

An analysis of the research where non-stationary models are presented for welding with a non-consumable and consumable electrode in argon, carbon dioxide, and their mixtures /12-14/ has showed that in these models, regardless of the welding method, the transfer of electrode metal and, accordingly, the increased effect of surfacing zones on the change in the balance of forces in the weld pool is not considered as a significant factor. Moreover, in these works there is no information on the calculation of the growth interval of the penetration zone before its termination and the causes of this phenomenon. This requires further studies on the formation of the penetration zone. For the case of surfacing with a consumable electrode under the flux layer, a detailed analysis of main force factors of the formation of the penetration zone and their distribution over the volume of the weld pool was not carried out to determine their effect on the movement of liquid metal and convective heat transfer, which did not allow to construct a non-stationary mathematical model for calculating the size of the penetration zone at $v_s = 0$ m/s, taking into account the force factors in the weld pool. Studies of the formation of the weld pool during electric arc welding and overlaying under a flux layer are devoted to works /15-18/ for wire and /19-21/ for strip electrode. However, during submerged arc welding it is very difficult to control, or even simply determine the main parameters that influence the evolution of the weld pool during the shaping period (Fig. 2).

The evolution of the interlayer of liquid metal under the arc is δ_l, and accordingly the penetration zone is determined by the dynamic balance of the metal-static pressure and the arc pressure on the weld pool. The main factor affecting the displacement of the liquid layer to the peripheral parts of the bath and the increase in the penetration depth after the start of the arc is its pressure on the base metal:

$$p_a = \frac{F_a}{S_a}, \quad (1)$$

where: F_a is the force of the arc; and S_a is the arc spot area.

The value of the arc spot area S_a is taken according to /22/. The change in S_a value with increase in the volume of molten metal is not taken into account.

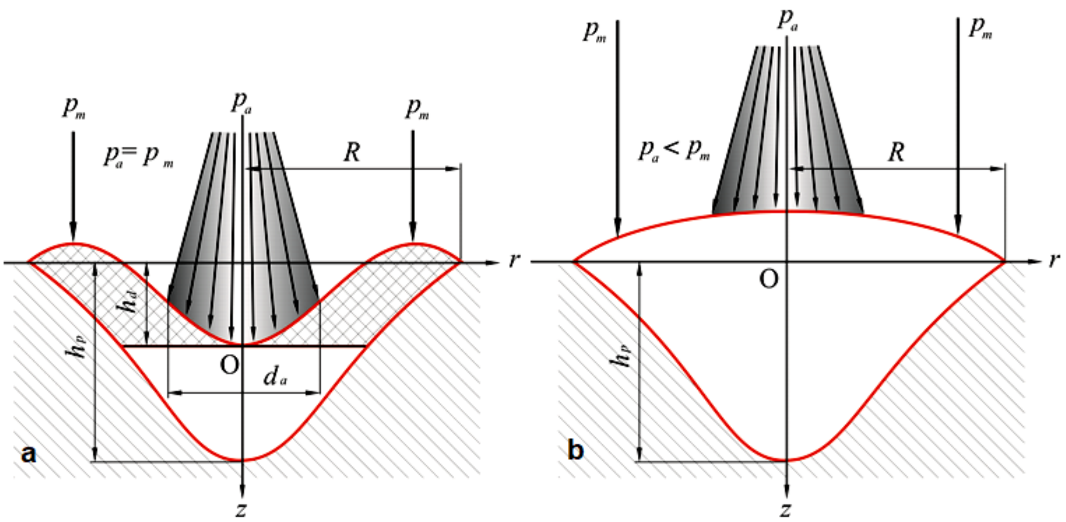

Figure 2. Scheme of pressure balance in the weld pool with stationary heat source for different points in time and pressure ratio in the weld pool: a) $p_m = p_a$; b) $p_m > p_a$.

Metal-static pressure p_m (Pa) can be determined from:

$$p_m = \rho g(h_{pr} + h_{rn} - \delta_l), \tag{2}$$

where: h_{pr}, h_{rn} are the penetration depth of the base metal and the height of the weld bead reinforcement, respectively.

Since the energy characteristics of the arc do not change at constant parameters of the surfacing mode, the penetration zone grows up to the moment at which the arc pressure is balanced by the metal-static pressure of the liquid metal (Fig. 3). After this moment, the arc will be forced upward and the metal of the liquid layer, filling the crater, will replenish exclusively the surfacing zone.

To determine the equilibrium point $p_a = p_m$, it is necessary to determine the functional dependence $p_m = f(t)$. We proceed from the assumption that increase in penetration depth stops when the arc exits to the surface of the base metal, so when

$$p_a = \rho g h'_{rn}, \tag{3}$$

where: h'_{rn} is the reinforcement magnitude, the metal-static pressure of which is equal to the arc pressure.

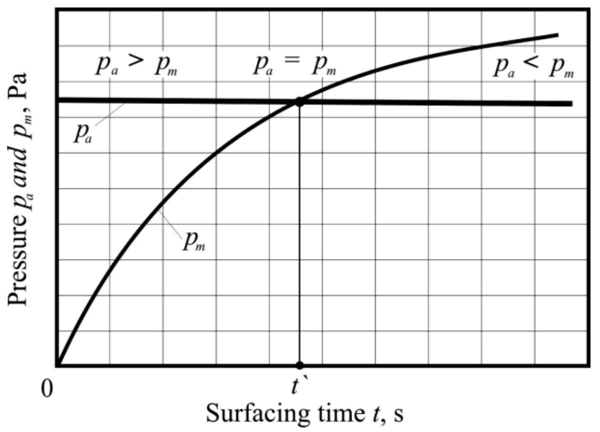

Figure 3. Diagram of pressure balance dynamics in the weld pool with a stationary heat source.

Given that the arc pressure can be defined as /23/:

$$p_a = 10^{-7} j_a I_s, \tag{4}$$

where: j_a is the average current density in the arc.

According to /24/, the value of j_a for arc surfacing is in the range $18\text{-}22 \cdot 10^6$ A/m^2. In calculations, the value $j_a = 20 \cdot 10^6$ A/m^2 is adopted.

RESULTS AND DISCUSSION

Thus, the value of penetration zone depth at which the growth of the penetration zone stops and the arc begins to be displaced upward by the molten metal of the weld pool, can be expressed by the following equation:

$$h_{pr} = \frac{p_a}{\rho g} - h'_{rn} + \delta_l. \tag{5}$$

To determine h'_{rn}, it is necessary to develop a technique for solving the equilibrium equation of the weld pool weld metal under non-stationary conditions.

To solve the equilibrium equation for the weld pool under the action of surface (interphase) tension forces and attractive forces, which has the form of a differential equation of the second degree, we use the variational-energy method according to the model described in /25/.

To obtain a particular solution and determine all sizes of a liquid droplet, boundary conditions must be specified corresponding to a certain arc of the integral curve. For these conditions, the cross-sectional area, S_w (m^2) and the diameter of the point B (m) liquid droplet, can be calculated or measured as a result of the experiment. To calculate these parameters, we use the volume equations of the rotation figure formed by a smooth second-order curve. Since the volumetric feed rate of the electrode metal is constant, the change in the volume of the deposited metal in time is linear, which allows us to determine the value of f_0 at any time during the formation of a stationary weld pool. The dimensionless analog of the gain of the deposited point is determined by the expression given below. Since the desired value of parameter c can be determined by Eq.(3), the calculation is stopped when the condition below is fulfilled,

$$c = \frac{h'_{rn}}{a_c}. \tag{6}$$

The calculation results according to the developed model show that the formation of a penetration zone in a wide range of mode parameters for the case of surfacing with a wire electrode under a flux layer practically coincides. Regardless of the electrode diameter and deposition mode parameters (in a certain range), the dynamics of the formation of the penetration zone correspond to the averaged dependence, confirms the validity of the approach used to model the formation of the penetration zone on an ongoing basis. A comparison of the calculated- and experimental data on the relative penetration depth h^* vs. the time of heating source action for surfacing with wire electrodes under the flux layer is shown in Fig. 4.

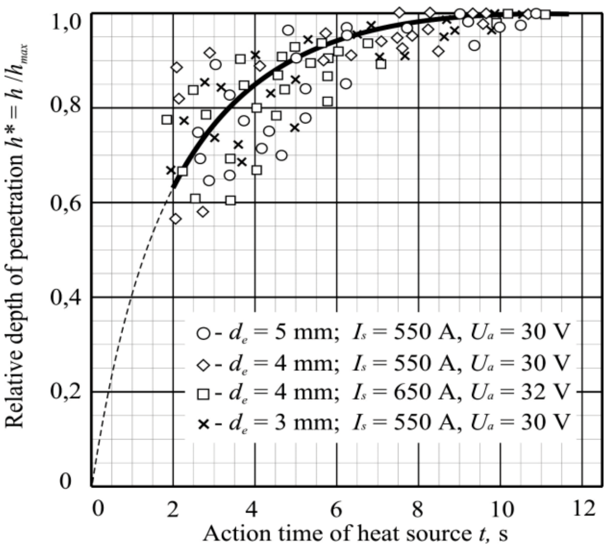

Figure 4. Calculated dependence of relative penetration depth on the duration of heating source compared to experimental data.

An analysis of the data shows that in an electric arc surfacing under a flux layer with wire electrodes, the increase in the depth of penetration of the base metal is completed in a period of 10-12 s, and in the first two seconds of the penetration zone formation, its dimensions reach values of at least 60 % of the limit for all surfacing options.

The result of the calculation according to the developed technique allows, therefore, to obtain the time instant t' as the initial parameter, upon reaching which the welding arc will be forced out onto the surface of the base metal and the penetration depth will stop growing.

This is a prerequisite for creating a new model of shaping of the weld pool in an unsteady mode, which will allow determining the parameters of the penetration zone and the weld zone in conditions of changing the power balance in the weld pool. The use of this model for the first time makes it possible to use the course of evolution of the penetration zone as one of the input parameters and establish the functional dependences of the size formation of deposited bead not only on the parameters of the surfacing mode, but also on the dependence of arc burning time. In addition, with the help of the developed model, it becomes possible to obtain by calculation the data on the formation of the weld pool with a fixed heat source, which previously could only be established experimentally.

The data on the formation of weld points at a zero value of the weld speed are important when making intermittent weld beads, as well as when making welded joints in the form of a point system (arc spot welding). In addition, the practical value of these data when surfacing rollers (when $v_s > 0$ m/s) is that, at the beginning and at the end of the weld for a certain time (Fig. 5), it is advisable to change the value of the surfacing speed to ensure constant dimensions as a penetration zone (penetration depth), and surfacing zone (bead width and height) along the entire length.

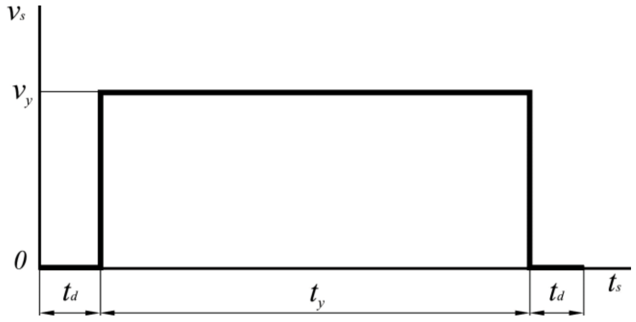

Figure 5. The cyclogram sample of the deposited bead with alignment of the penetration parameters along its length.

This will ensure dimensional stability of the weld bead, both in the area of constant parameters, and in the initial and final sections. This approach is of great importance for ensuring the quality of the deposited layer and will reduce the resource consumption of the recovery and strengthening processes by eliminating the re-surfacing operation and machining of excess deposited metal in these areas.

The application of the proposed calculation method will also allow to further increase the efficiency of electric arc welding with wire- and tape electrode under a flux layer using automated equipment, by creating the appropriate software for process control in real time.

CONCLUSIONS

Based on the balance of pressure in the welding arc and hydrostatic pressure of the liquid metal column in the crater of the weld pool, a mathematical model is developed for the shape evolution of the penetration zone during electric arc surfacing for a stationary and mobile heating source, which allows predicting the position and size of the melting front depending on the time of the heating source, and also allows to determine the moment of termination of penetration depth growth.

A new calculation method is proposed that allows one to determine the depth of the penetration zone of the base metal during electric arc surfacing, as based on the use of obtained data in the development of the penetration zone in time. This takes into account the time, as well as the size of the crater formed under the condition of zero deposition speed.

The developed mathematical model and the calculation methodology had made it possible to determine the shape of the penetration zone of the base metal during electric arc surfacing with a consumable electrode and showed good convergence with experimental data.

REFERENCES

1. Karkhin, V.A., Thermal Processes in Welding, Springer, Singapore, 2019. doi: 10.1007/978-981-13-5965-1

2. Liubov, B. (1989), *Mathematical analysis of heat conduction and diffusion processes in metallic materials*, Physics Metals Metal Sci. 1(67): 5-35. (in Russian).
3. Karkhin, V.A., Khomich, P.N., Ossenbrink, R. Mikhailov, V.G. (2007), *Calculation-experimental method for the determination of the temperature field in laser welding*, Welding Inter. 21(5): 387-390. doi: 10.1080/09507110701455574
4. Samotugin, S.S., Nesterov, O.Yu., Yarmitskii, A.G., Ivanov, V.P. (1999), *Optimization of plasma treatment conditions of tools*, Welding Inter. 13(1): 67-70. doi: 10.1080/0950711990945 2057
5. Gulakov, S.V., Chigarev, V.V., Ivanov, V.P., et al. (2004), *Improvement of technology for hardfacing of metallurgical equipment components*, Paton Welding Journal, 10: 54-57.
6. Ivanov, V., Makarenko, N.A., Lavrova, E., Ahieieva, M.V. (2020), *Electric arc deposition of an anticorrosive layer with two strip electrodes*, Solid State Phenom. 303: 39-46. doi: 10.4 028/www.scientific.net/ssp.303.39
7. Attey, D.R. (1980), *A mathematical model for fluid flow in a weld pool at high currents*, J Fluid Mech. 98(4): 787-801.
8. Kou, S., Wang, Y.H. (1986), *Computer simulation of convection in moving arc weld pools*, Metall. Mater. Trans. A, 17: 2271-2277. doi: 10.1007/BF02645925
9. Latif, J.M., Heat Convection, Springer-Verlag Berlin Heidelberg, 2006. doi: 10.1007/978-3-642-02971-4
10. Kumar, A., DebRoy, T. (2007), *Heat transfer and fluid flow during gas-metal-arc fillet welding for various joint configurations and welding positions*, Metall. Mater. Trans. A, 38(3): 506-519. doi: 10.1007/s11661-006-9083-4
11. Chernyshov, G.G., Sychev, M.P., Rybachuk, A.M. (1979), *Current distribution in the weld pool*, Automatic Welding, 11: 7-29. (in Russian)
12. Urusov, R.M., Sultanova, F.R., Urusova, T.E. (2012), *Numerical modelling of unsteady heating and melting of the anode by electric arc. Part 2. Numerical characteristics of the anode weld-pool*, Thermophys. Aeromech. 19(1): 149-162. doi: 10.1134/S0 869864312010167
13. Matsunawa, A., Yokoya, S., Asako, Y. (1988), *Convection in weld pool and its effect on penetration shape in stationary arc welds*, Quart. J Japan Weld. Soc. 6(4): 455-462. doi: 10.2207/q jjws.6.455
14. Ivanov, V.P., Lavrova, E.V., Il'yaschenko, D.P., Verkhoturova, E.V. (2020), *Modelling of fusion zone formation in shielded metal arc welding*, Struct. Integ. and Life, 20(3): 281-284.
15. Sudnik, V.A., Erofeev, V.A., Maslennikov, A.V., Tsvelev, R.V. (2015), *Modelling submerged arc welding process. Research of arc voltage and electrode diameter influence*, News TulGU, Tech. Sci. (Izvestiya TulGU. Tekhnicheskie nauki), 6(2): 12-21. (in Russian)
16. Li, X.R., Zhang, Y.M., Kvidahl, L. (2013), *Penetration depth monitoring and control in submerged arc welding*, Welding Journal, 92(2): 48-s-56-s.
17. Cho, D.-W., Song, W.-H., Cho, M.-H., Na, S.-J. (2013), *Analysis of submerged arc welding process by three-dimensional computational fluid dynamics simulations*, J Mater. Process. Technol. 213: 2278-2291. doi: 10.1016/j.jmatprotec.2013.06.017
18. Sengupta, V., Mendez, P.F. (2017), *Effect of current on metal transfer in SAW. Part 1: DCEP*, Weld. Journal, 96(7): 241s-249s.
19. Ivanov, V., Lavrova, E. (2018), *Development of the device for two-strip cladding with controlled mechanical transfer*, J Phys. Conf. Ser. 1059, 012020. doi: 10.1088/1742-6596/1059/1/012020
20. Lavrova, E.V., Ivanov, V.P. (2018), *Controlling the depth of penetration in the case of surfacing with a strip electrode at an angle to the generatrix*, Mater. Sci. Forum, 938: 27-32. doi: 10. 4028/www.scientific.net/MSF.938.27
21. Ivanov, V., Lavrova, E., Burlaka, V., Duhanets, V. (2019), *Calculation of the penetration zone geometric parameters at surfacing with a strip electrode*, East.-Europ. J Enterp. Technol. 6(5)(102): 57-62. doi: 10.15587/1729-4061.2019.187718
22. Razmyshlyaev, A.D., Automatic submerged arc welding by tape electrode (Avtomaticheskaya elektrodugovaya naplavka lentochnym elektrodom pod flyusom), Mariupol', GVUZ «PGTU», 2013. (in Russian)
23. Lebedev, V.K., Pentegov, I..V. (1981), *Force effect of the welding arc*, Automatic Welding, 1: 7-15. (in Russian)
24. Razmyshlyaev, A.D., Physical foundations of the shaping of beads and seams during arc surfacing and welding with control actions (Fizicheskie osnovy formoobrazovaniya valikov i shvov pri dugovoj naplavke i svarke s upravlyayushchimi vozdejstviyami), Doctoral Dissertation, Mariupol, 394 p., 1996. (in Russian)
25. Berezovsky, B.M., Mathematical models of arc welding: In 3 vol.-vol.1. Mathematical modelling and information technology, models of the weld pool and the formation of the seam (Matematicheskie modeli dugovoj svarki. V 3 t.-t.1. Matematicheskoe modelirovanie i informacionnye tekhnologii, modeli svarochnoj vanny i formirovaniya shva), Chelyabinsk, Publishing House of YUUrGU, 585 p., 2002. (in Russian)