Представлені методи математичного моделювання геометричних характеристик наплавлених поверхонь, що дозволяють спрогнозувати результат експериментальних досліджень. Визначено точність існуючих способів оцінки геометричних параметрів зони проплавлення.

Встановлено, що використовуючи схему розподілу джерела нагріву по прямокутної області вдалося наблизити розрахункові дані до експериментальних в діапазоні швидкостей наплавлення 6–12 м/г. При параметрі розподілу джерела нагріву по ширині 1,5 мм максимальна розбіжність розрахункових і експериментальних значень глибини проплавлення, не перевищує 15 % для стрічок шириною від 60 до 90 мм. Це пояснюється тим, що дана модель адекватна тільки для холоднокатаних стрічкових електродів суцільного перетину. Досліджено розрахункова схема розподілу температур в напівнескінченому тілі від рухомого лінійного джерела тепла з розподілом температури по ширині, що дозволяє адекватно оцінити глибину проплавлення основного металу при наплавленні стрічковим електродом. Дуга, яка переміщається по торцях стрічки, не утворює значного кратера, як при наплавленні дротяним електродом. Ефективність передачі тепла від дуги до основного металу визначається конвекцією рідкого металу в активній частині ванни, яка зменшується при малих швидкостях наплавлення. Рух металу в цій зоні пов'язано з рухом його по всьому об'єму зварювальної ванни. Встановлено, що зниження температури металу в рідкому прошарку зварювальної ванни в межах 300–500 °C при використанні стрічкового електрода в порівнянні з дротяним пов'язано з явищем переміщення дуги по торцю стрічкового електрода і зміною коефіцієнта зосередженості джерела тепла

Ключові слова: стрічковий електрод, розподіл температур, напівнескінченне тіло, глибина проплавлення, джерело нагріву

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CALCULATION OF THE PENETRATION ZONE GEOMETRIC PARAMETERS AT SURFACING WITH A STRIP ELECTRODE

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1. Introduction

Current trends to improve the efficiency in recovering worn surfaces and in preventing the development of dangerous defects while maintaining the required operational properties of the surfaced layer are characterized by extensive use of mathematical modeling for the elements of the technological process. Predicting the structure and properties of the surfaced layer is an important and complex research task, due to the large number of factors that influence its application process.

Modeling the shape formation of a weld pool and the formation of penetration and surfacing zones makes it possible to quantify the parameters of a joint and a near-joint zone without conducting expensive experimental studies and provides additional possibilities to control the composition and properties of the surfaced metal.

One of the ways to extend the technological capabilities of surfacing under the flux by a strip electrode in the restoration and strengthening of working surfaces is the use of controlled mechanical transfer of an electrode metal. The benefits of using it at surfacing under the flux were shown for both one [1] and two strip electrodes [2]. In this case, it is possible to ensure a more even distribution of thermal energy along the width of the weld pool, as well as when changing the angle of the strip's turn relative to the surfacing vector [3], as well as adjust the heat flow by the depth of the penetration zone. In this regard, it is a relevant task for modern production of metallurgical and machine-building equipment to undertake a study into the impact of parameters of the transfer of an electrode metal to the heat input to the main metal and the geometric parameters of the surfaced roller.

2. Literature review and problem statement

The shape formation of the penetration zone and the effect exerted on this process by the transfer of an electrode metal at surfacing with strip electrodes were addressed in a significantly less number of studies than for that with a wire electrode, especially with the comparison of estimated and experimental data on the geometric parameters of the penetration zone.

Paper [4] reports results from studying an analysis of the convergence between the estimation data based on the equations of heat distribution in a semi-infinite body from a powerful fast-moving source of finite width and the experimental contours of weld pools, obtained by splashing at surfacing with a strip electrode made from steel 08kp with a thickness of 0.5 mm under the fluxes AN–348A and ZhSN–1 on reverse polarity. Study [5] gave results from an analysis that established that the estimated values of the pool shape (in plane $z=0$), as well as its width and length are in a satisfactory agreement with data from the experiment at certain values of the thermal-physical constants. But, at the same time, the authors indicated that there is a significant (by 5÷10 times) discrepancy between the estimated and experimental values of depth and penetration area of the main metal.

Paper [6] reports results of research into control over the depth of penetration and the share of the main metal's participation by changing the parameters of the mode at MIG and TIG–welding with a wire electrode [7, 8]. However, the dynamic properties of the power source were not investigated regarding a strip electrode. Studies [9, 10] continued to analyze the parameters of the MIG welding technological process and compared the estimation data with the results from experiments. However, when using a strip electrode, one needs to consider arc displacement along the end of the strip. Study [11] constructed a complete two-dimensional mathematical model of the weld pool, taking into consideration the distribution of the thermal power of the heating source according to normal law. Such a distribution law cannot be used for strip electrodes because the character of heat distribution differs from a normal one. At the same time, work [12] indicates that the weld pool shape formation process is a complex dynamic object with strong non-linearity, multi-parametric internal connections, and a multitude of random and uncertain factors. Simulation based on the theory of a non-linear systems control can overcome these difficulties. This very approach is used in the study of the dynamic characteristics of controlled transfer at welding using a wire electrode [13]. However, such possibilities in the use of a strip electrode for electric arc surfacing were not explored previously. This is due to the lack of an adequate mathematical model, even though the process of surfacing under the flux with a strip electrode is common in the restoration of working surfaces.

Paper [14] reports a numerical simulation of the penetration zone based on convection; the authors adopted in the estimation schemes that the main force factors are those that act in the opposite direction to all other force factors. Work [15] continued the studies whose authors, by assuming the asymmetrical distribution of flows from force factors at a stationary heat source, investigated the effect of welding speed. The problems described in [16] assumed the existence of an even flow of speed along the coordinate axes. In both cases, the distribution of velocities took the form typical of similar models with a turn in the tail part, predetermined by the condition for flow continuity. In contrast to other similar works, [17] notes that a metal flow is generated in the same direction in which the heat source moves. At the same time, the reported scheme of the estimation model would increase the flow rate when it moves inwards [18]. The reason for this could be the models used for the distribution of electromagnetic forces. The cause of this phenomenon might be a change in the distribution of electromagnetic forces and the proportion of the electric-slag process.

Therefore, it is necessary to study the causes of discrepancies between estimation and experimental data on the geometric parameters for a penetration zone at surfacing with a strip electrode.

3. The aim and objectives of the study

The aim of this study is to assess the geometric parameters of the penetration zone at surfacing with a strip electrode using different diffusion transfer models and to compare estimation data with the results from experiment. An adequate forecast of geometric parameters of the penetration zone would make it possible to determine the parameters for a surfacing mode with a minimum value of the share of the main metal and to eliminate the emergence of unacceptable defects in the surfaced layer.

To accomplish the aim, the following tasks have been set:

– to investigate the estimation scheme for building a temperature distribution in a semi-infinite body from a movable linear heat source with the distribution of temperature over the predefined width;

– to investigate the results of dependence of the temperature of a liquid layer near the crater of a weld pool in a semi-infinite body on the linear source at surfacing with a strip electrode;

– to investigate the mathematical model of heating a semi-infinite body.

4. Methods to study the penetration depth of the main metal

To solve the set tasks, we compared the estimation data, acquired from mathematical modeling, with experimental values.

The experimental contours of weld pools were derived by splashing at surfacing on plates made from steel St3 by strip electrodes 08kp, the sizes of 40×1.0 mm and 45×0.5. The surfacing was performed using the self-propelled automated device, type A–874N, voltage on arc U_a=30–36 V, welding current I_s=500–650 A. The used source of a welding current was the rectifier VDU–1201.

The principle of modeling taken as the basis was the thermal processes in a metal at surfacing. An analysis of these processes would make it possible to establish a correlation between modelling results and experimental data, when the convergence between results would be quantified based on indicators to be reflected graphically. A prerequisite for data correlation is the convergence between experimental and estimation data within the closest values.

The method of weld pool splashing was applied to derive the values of penetration depth for different surfacing speeds v_s=4–12 m/h and a width of the strip electrode of 60 mm.

Experimental curves are built on averages of at least three results from the same data measurement.

During mathematical modeling, we solved problems on heating a semi-finite body of the continuously enabled source. The initial body temperature would be accepted equal to T_0, and the surface of the body would be considered thermally-insulated. Given the proposed scheme of the body and a high thermal conductivity of low-carbon steel compared to a Newton's coefficient, replacing the boundary conditions of third kind with the simpler thermal insulation conditions would produce an error in determining the temperature that does not exceed 5 %.

The basic formula used was the solution to the thermal conductivity equations in the form [5]:

$$\frac{\partial T}{\partial t} = a\nabla^2 T + v\frac{\partial T}{\partial x} + \frac{F(x,y,z,\tau)}{c\rho}, \tag{1}$$

where $T = T(x_0, y_0, z_0, t)$ is the body temperature, calculated based on the initial temperature (heating temperature), K; $F(x, y, z, t)$ is the volumetric density of a heat source, W/m^3.

The distribution of a temperature field was calculated in relation to steel St3, so the following values for the thermal physical constants were accepted: thermal conductivity λ=40 W/m·K; values $c\rho$=4.9·10^6 J/m^3·K. The width of an electrode strip for surfacing, which expresses the length of a source, is $l_0 = 6\cdot 10^{-2}$ m, the surfacing speed is v_s=3·10^{-3}. The power of a source Γ (W/m) was determined based on the surfacing mode parameters.

5. Results of studying the estimated penetration depth of the main metal depending on the parameters of a source power distribution

5. 1. Results of studying the estimation scheme for building a temperature distribution in a semi-infinite body

When solving the problem on constructing the distribution of temperatures in a semi-infinite body depending on a movable linear heat source with a temperature distribution over the predefined width, we built an estimation diagram (Fig. 1), where a linear δ-shaped source of power q and length l_0 is located at the surface of a body perpendicular to the x axis symmetrically relative to it and moves in the direction of the axis at speed v_s.

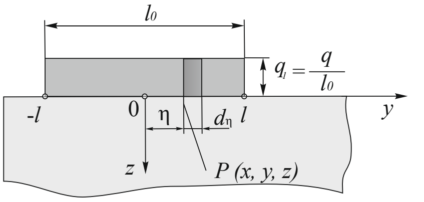


Fig. 1. Estimation diagram for building the distribution of temperatures in a semi-infinite body depending on a movable linear heat source with the distribution of temperature for width l_0

The function of coordinates and time $F(x, y, z, t)$ shall be represented in the following form:

$$F(x,y,z,t) = 2\Gamma\delta(x - v_s t)\pi(\eta)\delta(z), \tag{2}$$

where $\Gamma = \frac{q_u}{l_0}$ is the power given to the body by a unit of length of the heat source, W/m; $\pi(\eta)$ is the unity function that takes into consideration the resulting length of a source; η is the coordinate of width of a strip electrode along the y axis, m; q is the part of this power that acts directly on metal heating; l_0 is the width of a strip electrode, m.

$$\pi(\eta) = \begin{cases} 1, & \frac{l_0}{2} \le \eta \le \frac{l_0}{2}, \\ 0, & |\eta| > \frac{l_0}{2}. \end{cases} \tag{3}$$

To account for the influence from the body's boundaries next to actual sources, we introduced a mirror source, the result being a coefficient of 2 introduced to (2).

5. 2. Results from solving a thermal conductivity equation taken as the basic one

A solution to equation (1) is derived from the following formula:

$$T(x_0, y_0, z_0, t_0) = \frac{1}{c\rho}\int_0^t \int \int_{-\infty}^{\infty} \begin{matrix} G(x_0, y_0, z_0, x, y, z, t)\times \\ \times F(x, y, z, \tau) \end{matrix} \mathrm{d}x\mathrm{d}y\mathrm{d}z\mathrm{d}t, \tag{4}$$

where G is the Green function for unlimited space [19]:

$$G(x,y,z,t) = \frac{1}{\left[4\pi a^2 (t_0 - t)\right]^{3/2}} \times \\ \times \exp\left[\frac{(x_0 - x)^2 + (y_0 - y)^2 + (z_0 - z)^2}{4a^2 (t_0 - t)}\right]. \tag{5}$$

By assuming the quasi-stationary character of temperature distribution, we believe that at each instantaneous position of the source there is enough time to establish a stationary distribution of temperature and, therefore, in a time interval (4) one can set the upper boundary $t=\infty$. Introduce a system of coordinates $x=x_0-v_s t$, $y=y_0$, $z=z_0$, which moves along with the source of heating, then:

$$T(x_0, y_0, z_0, t) = \frac{\Gamma}{2\pi\lambda}\exp\left[-\frac{(\upsilon_{\text{н}} x)}{2a^2}\right] \times \\ \times \int_{-l_0/2}^{l_0/2} \frac{\exp\left[-\frac{\upsilon}{2a^2}\sqrt{x^2 + (y + \eta^2) + z^2}\right]}{\sqrt{x^2 + (y + \eta^2) + z^2}} \mathrm{d}\eta. \tag{6}$$

For the convenience of calculating a temperature change in a semi-infinite body at surfacing, the accepted unit of all lengths was a value l_0.

Using a rectangular source makes it possible to change the character of the source distribution due to three parameters: t_{0i}, h_1, h_2. In order to further approximate the estimated data on penetration depth h_p, it is accepted in experimental data that a thermal flow is distributed over the surface of a rectangle with the predefined length h_1 and width h_2.

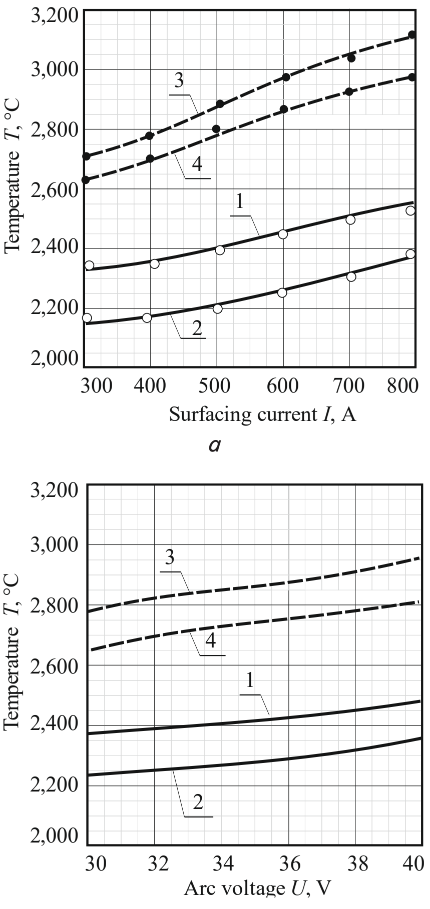
A mathematical model based on the Green function in a movable coordinate system for a continuously functioning rectangular source takes the form [9]:

$$T(x,y,z,t)= \\ =\frac{\eta q_u}{16c_\rho h_1 h_2\sqrt{\pi a}}\times \\ \frac{1}{\sqrt{t+t_{0z}}}\left\{\operatorname{erf}\left[\frac{y+h_1}{2\sqrt{a(t+t_{0y})}}\right]-\operatorname{erf}\left[\frac{y-h_1}{2\sqrt{a(t+t_{0y})}}\right]\right\}\times \\ \times\int_0^t\times\left\{\operatorname{erf}\left[\frac{x+h_2+v_{н}t}{2\sqrt{a(t+t_{0x})}}\right]-\operatorname{erf}\left[\frac{x-h_2+v_{н}t}{2\sqrt{a(t+t_{0x})}}\right]\right\}\times \\ \times\sum_{n=-m}^{m}\exp\left[-\frac{(z+2nL)^2}{4a(t+t_{0z})}\right]\mathrm{d}t, \qquad (7)$$

where t_{0x}, t_{0y}, t_{0z} is the action time of a fictitious source, which characterizes its concentration and ensures a normal distribution of thermal power along the appropriate coordinate, s; L is the thickness of a heated layer, m.

5. 3. Results that illustrate the temperature dependence of a liquid layer near the crater of a weld pool in a semi-infinite body on the linear source

Results that illustrate the temperature dependence of a liquid layer near the crater of a weld pool in a semi-infinite body on the linear source at electric arc surfacing are shown in Fig. 2.



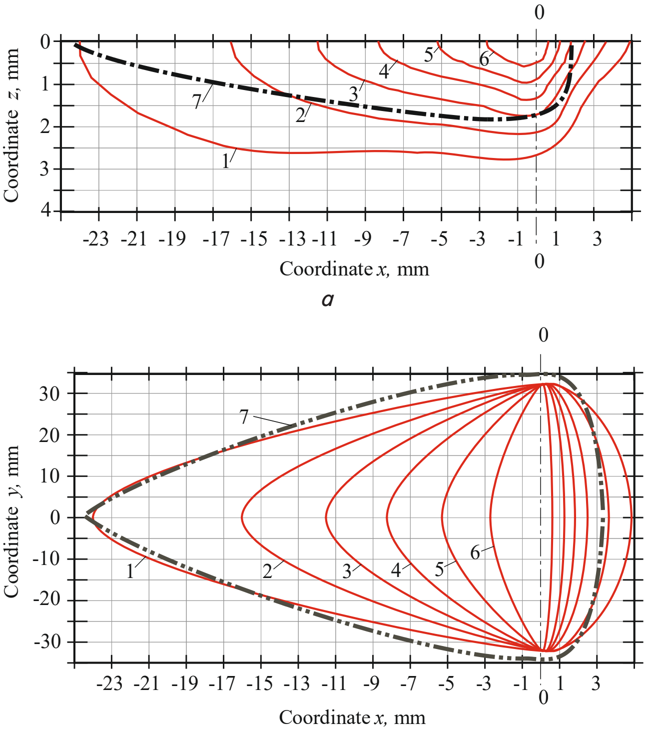
a

b

Fig. 2. Dependence of the estimated temperature of a liquid metal at a distance of ten times the thickness of the strip (10δ) on: *a* – welding current at U_a=32 V; *b* – arc voltages at I_s=500 A; 1 – strip electrode, 45×0.5 mm; 2 – strip electrode, 40×1.0 mm; 3 – wire, d_e=3 mm; 4 – wire, d_e=4 mm

Fig. 2 shows a dependence of the estimated temperature of a liquid metal at a distance of ten times the thickness of the strip on welding current (Fig. 2, *a*) and on arc voltage (Fig. 2, *b*) for strip electrodes of different cross-sections, namely, 45×0.5 mm and 40×1.0 mm, as well as wires, 3 mm and 4 mm in diameters. As the thickness of the strip electrode increases, the estimated temperature values of a liquid metal decrease. For example, if one uses the 0.5 mm thick strips, then T=(2,150–2,400) °C, and for strips that are 1.0 mm thick, T=(2,340–2,510) °C. Similarly, when using a wire of d_e=3 mm, then T=(2,700–3,120) °C, and for a wire with a larger diameter d_e=4 mm, T=(2,640–2,950) °C.

We have determined a functional ratio of parameters for the distribution of a heating source depending on the technological mode of surfacing. The result of calculation is the derived dimensions of a penetration zone, which are close to experimental values under conditions of a stationary weld pool (Fig. 3, 4).



a

b

Fig. 3. Estimation contours of isotherms for a strip with the cross-section 60×0.5 mm: *a* – in the *x*0*z* plane; *b* – in the *x*0*y* plane (strip 08kp, flux AN–60, η_i=0.8; I_s=500 A; U_a=32÷35 V; v_s=10 m/h; y=0(*a*); z=0(*b*)): 1 – T=1,770 K; 2 – T=2,500 K; 3 – T=3,300 K; 4 – T=4,100 K; 5 – T=4,900 K; 6 – T=5,700 K; 7 – experimental data

Fig. 4 shows dependences of penetration depth of the main metal on the speed of surfacing and the width of a strip. As the surfacing speed increases to 12 m/h (Fig. 4, *a*), the penetration depth of the main metal is reduced to (1.8–0.8) mm for the applied parameters h_1=(0.5–1.5) mm, respectively. A similar dependence was derived when studying the dependence of penetration depth on the width of a strip electrode (Fig. 4, *b*).

Thus, we have established a dependence of the estimated penetration depth of the main metal on the parameters of a source power distribution. The importance of taking into consideration the influence of convection flows of a liquid metal in a weld pool at surfacing with a strip electrode has been revealed.

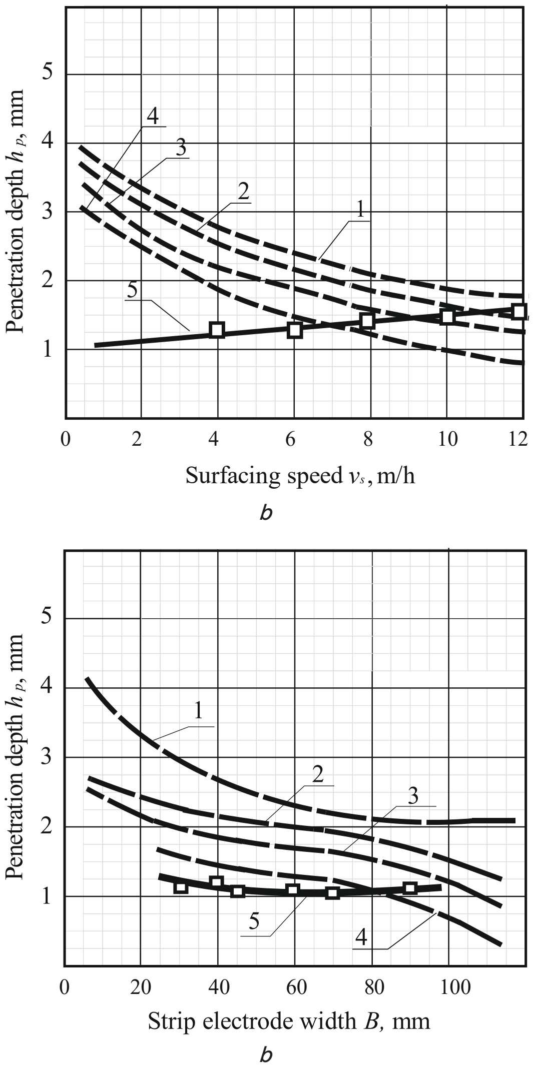


Fig. 4. Dependence of penetration depth of the main metal for a strip of 60–0.5 mm on: *a* – the speed of surfacing; *b* – the width of the strip, δ=0.5 mm, I_s=800÷850 A, v_s=10 m/h; (U_a=28–30 V); 1 – estimation data in line with a linear source scheme; 2, 3, 4 – estimation data using a parameter h_1=0.5; 1.0; 1.5 mm; 5 – experimental data

6. Discussion of results of studying the penetration depth of a main metal depending on the parameters of a source power distribution

Practically linear dependences of maximum temperature on all the parameters, shown in Fig. 2, indicate a low degree of adequacy of the examined models of conductive thermal transfer to the actual surfacing conditions.

At the same time, our data from calculations revealed a significant dependence of the estimated penetration depth of a main metal h_p on the parameters of a source power distribution over the area of a rectangle (Fig. 3). Convergence between the estimated and experimental data, given the actual changes of parameter *h* due to a welding current magnitude, is quite satisfactory.

Significant discrepancy between the estimated and experimental values for h_p at a stationary arc and low surfacing speeds (Fig. 3) relates to a growth in the thickness of a liquid metal layer on the front wall of the crater (δ_p). Features in the strip electrode melting lead to that the arc pressure on a main metal at surfacing with a strip under equal conditions is less than that at surfacing with an electrode wire. The arc, which moves along the end of the strip, does not form a significant crater, as is the case at surfacing with a wire electrode. The arc in the form of pulses heats the volumes of a liquid under the electrode. In this case, the efficiency of heat transfer from the arc to a main metal is determined by the convection of the liquid metal in the active (head) part of the pool, which decreases at low surfacing speeds. That is, the source of heat under the electrode is a liquid (overheated) metal. The movement of a metal in this local zone relates to its movement throughout the entire volume of a weld pool. When a surfacing current increases, the streams that develop in the liquid metal under the influence of Lorenz forces contribute to its outflow from the head part, increase convection flows in the liquid layer under the arc (electrode) and improve the efficiency of main metal penetration, h_p (Fig. 4).

By using a scheme of the heating source distribution over the rectangular area, it was possible to bring the estimated data closer to experimental in the surfacing speed range of 6–12 m/h (Fig. 4, *a*). At the parameter for a heating source distribution over width of 1.5 mm (Fig. 4, *b*, curve 4), the maximum divergence between the estimated and experimental values of penetration depth does not exceed 15 % for strips with a width of 60 to 90 mm. However, when using narrow strips (up to 40 mm wide) and low surfacing speeds (up to 6 m/h), it is necessary to adjust the concentration parameters of a heating source to derive adequate results.

A given model is suitable only for cold-rolled solid strip electrodes. For the case of using metallic-ceramic or powder strips, it is necessary to adjust the distribution function of a heat flow to the parameters of efficiency in penetrating the main and electrode metal.

7. Conclusions

1. We have investigated the estimation scheme of temperature distribution in a semi-infinite body depending on a movable linear heat source with the distribution of temperature for width, which makes it possible to adequately estimate the penetration depth of a main metal at surfacing with a strip electrode.

2. A decrease in the temperature of a metal in the liquid layer of a weld pool within 300–500 °C when using a strip electrode, compared to a wire electrode, is due to the phenomenon of arc moving along the end of the strip electrode and a change in the ratio concentration of a heat source.

3. We have examined a mathematical model of heating a semi-infinite body by a linear source of heat with a change in the concentration ratio over its width. The application of the distribution of a heat flow over a rectangular area makes it possible to improve the accuracy of temperature field simulation both along the surface plane of the main metal and over the depth of the penetration zone. At a value for the heating distribution ratio over a source width of 1.5 mm in the surfacing range of 6–12 m/h, we have derived the estimation data that are close to experimental.

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