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 the arrangement 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 characteristic 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 surfacing under the flux with a strip electrode.

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 40x1.0 mm and 45x0.5. The surfacing was performed using the self-propelled automated device, type A–874N, voltage on arc: $U_{a}=30–36$ V, welding current $I_{t}=500–650$ 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 modeling 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]:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{\partial T}{\partial x} + F(x, y, z, t) \frac{\partial}{\partial x},$$  \hspace{1cm} (1)

where $T=T(x, y, z, t)$ 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 the following form [5], based on the initial temperature (heating temperature), $K$; $F(x, y, z, t)$ is the volumetric density of a heat source, W/m$^3$.

$$T(x, y, z, t) = \frac{\Gamma}{4\pi \alpha t} \exp \left\{ -\frac{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2}{4\alpha t} \right\} \times$$

$$\times \left[ \frac{\eta^2}{2a^2} \sqrt{x^2 + (y + \eta)^2 + z^2} \right]$$  \hspace{1cm} (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: $t_0$, $l_1$, $l_2$. 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 $l_1$ and width $l_2$.

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

$$G(x, y, z, t) = \frac{1}{4\pi \alpha t} \exp \left\{ -\frac{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2}{4\alpha t} \right\} \times$$

$$\times \left[ \frac{\eta^2}{2a^2} \sqrt{x^2 + (y + \eta)^2 + z^2} \right]$$  \hspace{1cm} (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 integral $t = t_0$.

Introduce a system of coordinates $x = x_0 - \eta \phi, y = y_0, z = z_0$, which moves along with the source of heating, then:

$$T(x, y, z, t) = \frac{\Gamma}{2\pi \alpha} \exp \left\{ -\frac{(x-x_0)^2}{2a^2} \right\} \times$$

$$\times \left[ \frac{\eta^2}{2a^2} \sqrt{x^2 + (y + \eta)^2 + z^2} \right]$$  \hspace{1cm} (6)

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 $l$.
where \( t_{0y} \), \( t_{1y} \), \( t_{2y} \) is the action time of a fictitious source, which characterizes its concentration and ensures a normal distribution of thermal power along the appropriate coordinates, \( \eta \); \( L \) 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.

\[
T(x, y, z, t) = \frac{n \eta}{16 \nu \beta \kappa \sqrt{2\pi}} \times \\
\frac{1}{\sqrt{\pi} \tau_z} \left\{ \text{erf} \left[ \frac{y + h_z}{\sqrt{\nu \beta (t + \tau_z)}} \right] - \text{erf} \left[ \frac{y - h_z}{\sqrt{\nu \beta (t + \tau_z)}} \right] \right\} \times \\
\times \sum_{a} \exp \left[ -\frac{(z + 2nL)^2}{4\nu \beta (t + \tau_z)} \right] dt,
\]

\( \tau_z \) is the action time of a fictitious source, \( \eta \) is the concentration of its heating power, \( L \) is the thickness of the heated layer, m. \( \nu \beta \) is the thermal diffusivity of the material, m\(^2\)/s.

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 \( T = (2,150–2,400) ^\circ \text{C} \), and for strips that are 1.0 mm thick, \( T = (2,340–2,510) ^\circ \text{C} \). Similarly, when using a wire of \( d_e = 3 \) mm, then \( T = (2,700–3,120) ^\circ \text{C} \), and for a wire with a larger diameter \( d_e = 4 \) mm, \( T = (2,640–2,950) ^\circ \text{C} \).

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).

Fig. 3. Estimation contours of isotherms for a strip with the cross-section 60×0.5 mm: a — in the \( xOz \) plane; b — in the \( xOy \) plane (strip 08kp, flux AN-60, \( \eta = 0.8 \); \( L = 500 \) A; \( U_e = 32–35 \) V; \( v_e = 10 \) 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 \( h_e = (0.5–1.5) \) 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, J=800–850 A, ν=10 m/h; (U=28–30 V); 1 – estimation data in line with a linear source scheme; 2, 3, 4 – estimation data using a parameter h=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 h₀ 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 h₀ 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 (h₀). 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, h₀ (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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