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MODELING THE TECHNOLOGY OF DEPOSITION OF A LAYER OF VARIABLE CHEMICAL COMPOSITION

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It is shown that the nature of the change of chemical composition of the weld (deposited metal) is determined by the law of control of volume feed rate of the alloying electrode, which was derived by mathematical modeling of the effect of surfacing technology on the process of weld pool alloying. It is found that the high gradient of charge of chemical composition along the weld length is ensured by a discrete change of the volume feed rate of the alloying electrode. At a rectangular waveform of the electrode feed pulse, the alloying element distribution in the weld metal is asymmetrical at the stage of increase and decrease of the concentration that is manifested to a greater extent with increase of weld pool volume. Experimentally confirmed calculation results are presented, which show that the trapezoidal shape of the pulse allows reducing the asymmetrical nature of change of the composition. It is found that the nature and gradient of alloying element distribution in the weld can be changed at pulsed feed of the alloying electrode by a sinusoidal law. Conditions of forming a deposited layer of variable composition and hardness along the length of the barrel of a roll of continuous billet mill were determined. 12 Ref., 1 Table, 7 Figures.

Keywords: *mathematical modeling, weld pool, deposited metal, variable chemical composition, alloying electrode, feed pulse shape, forming roll, variable hardness along the barrel length*

Application of a technology which allows changing the metal composition during welding (surfacing) [1, 2] is largely determined by the ability to provide the specified changes of alloying element content in the transition areas, as well as stabilization of the composition between these areas [3]. At the same time, it is necessary to take into account the fact that deviation of weld metal composition from the required one can be caused by changes of mode parameters. This is related to deviations in product geometry, errors in equipment setting up, as well as possible voltage fluctuations. Moreover, change of the mode parameters can be related to a change of the processed surface curvature, which affects the conditions of weld pool formation [4]. Here, it should be noted that solution of the problem of geometrical adaptation of welding speed vector (deposition of working layers) of a complex configuration, is provided by process control system, automated and robotic equipment. Application of programming by off-line and on-line methods, and well as contact and contactless sensors, and arc tracking devices, allows controlling complex movements of the welding torch in space. In contrast, the process of technological adaptation is difficult to automate. Moreover, deviations of mode parameters, even in case of their successful adaptation, will inevitably lead to changes in metal composition under changed environmental conditions.

At the same time, such changes can be performed purposefully, so as to ensure the correspondence of the distribution of metal properties to the nature and intensity of loading. In work [5] a calculated dependence was derived by processing the experimental data, in order to perform an approximate assessment of the nature of the change of alloying element concentration in the metal at linear increase of its content in the electrode from X up to Y. Proceeding from processing results, the law of concentration change in the weld, close to the exponential one, is characterized by linear dependence of the angle of inclination of the tangent to the exponent $(Y–X)/D = \mathrm{tg}\alpha$, where D is the characteristic length of the area of transition from X to Y, α is the angle which determines the gradient of the rate of alloying electrode feeding into the pool. Much more complicated is the problem of development of an adequate mathematical model that allows prediction of the effect of the change of alloying conditions during surfacing on the weld chemical composition, in particular at a high speed of these changes. In [6] volume rate of alloying element feeding into the pool and weld pool dimensions (volume) are considered as input parameters for modeling the alloying process at deposition of metal of variable chemical composition. However, application of these models for development of variants of the technology of deposition of a working layer of a variable composition and properties requires studying the effect of volume rate of alloying element feeding into the weld pool on their content in the weld. The objective of the work was to study in a mathematical model the possibilities of controlling the process of alloying welds of a variable chemical composition and properties.

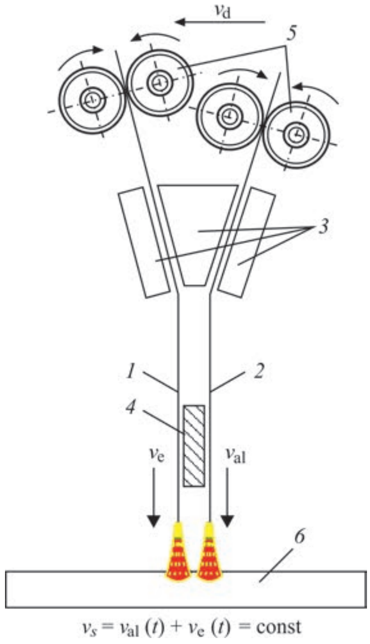

Figure 1. Scheme of deposition by two strip electrodes: *1* — low-alloyed electrode, *2* — alloyed electrode; *3* — guides; *4* — current conduit; *5* — feed rollers; *6* — base metal; v_d — deposition rate

Modeling conditions envisage feeding into the pool a constant volume of two electrodes differing by their chemical composition, while the total mass feed rate remains constant at the change of feed rate of each of them (Figure 1). Change of concentration $C(t)$ in the transition area depends on volume rate of alloying element feed, and degree of its absorption from the electrode and flux. In addition, weld dilution by base metal (previous layer) is taken into account, as well as buffering effect of pool volume (V) that limits the possibility of high alloying gradients. For a quasistationary state of the pool, when its volume can be taken constant, the following dependence for calculation of the change of composition $C(t)$ in the transition area was obtained from the equation of alloying element material balance in [6]:

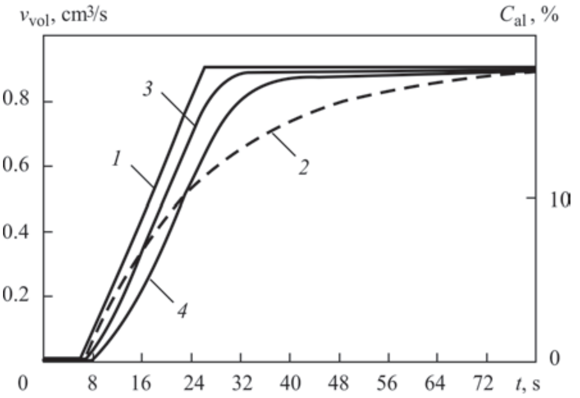

Figure 2. Dependence of the nature of weld composition change $C(t)$ on the law of the change of volume rate of alloying electrode feed $v_{al}(t)$: *1* — law of the change of $v_{al}(t)$; *2* — $C(t)$ calculation by the data of [5]; *3* — calculation by dependence (1) for $V = 2$ cm^3; *4* — same, for $V = 5$ cm^3

$$C(t) = e^{-\frac{v_d}{V}t} \times$$
$$\times \left\{ \begin{array}{l} \int\limits_0^t \left[v_{al}(t) C_{al} \eta_e + v_s k_f C_f \eta_f + C_{bm}(t) v_{bm} \eta_{bm} \right] \times \\ \times \frac{1}{V} e^{\frac{v_d}{V}t} dt + C_0 \end{array} \right\}, \quad (1)$$

where C_{al}, C_f, $C_{bm}(t)$ is the volume concentration of the alloying element in the electrode, flux and its distribution in the base metal (previous layer); η_e, η_f, η_{bm} — are the coefficients of element transition from the electrode, flux, base metal; k_{fl} is the relative mass of the flux; $v_d(t) = v_s + V_{bm}(t)$ is the volume deposition rate; $v_{bm}(t)$ is the volume rate of base metal penetration; $\gamma(t)$ is the fraction of base metal participation in the weld; $v_s = v_{al}(t) + v_e(t) = \mathrm{const}$ is the total volume rate of electrode feed; $v_{al}(t)$, $v_e(t)$ is the volume feed rate of electrode that contains the alloying element, and does not contain it, respectively; C_0 is the integration constant.

By the given law $C(t)$, taking into account the known parameters of the deposition process, the rate of alloying electrode feed, $v_{al}(t)$ is determined using the dependence derived in [6]:

$$v_{al}(t) = \frac{1}{C_{al}\,\eta_e} \times$$
$$\times \left\{ V \frac{dC(t)}{dt} - \left[v_s k_f C_f \eta_f + C_{bm}(t) v_{bm} \eta_{bm} - v_d C(t) \right] \right\}. \quad (2)$$

Dependencies (1), (2) allow more adequate prediction of the nature of concentration change both at the increase and at the decrease stage, depending on the change of alloying electrode feed rate. With increase of its feed rate by a linear law (Figure 2, curve *1*) the nature of variation of the composition, derived by calculation by dependence (1) depends on weld pool volume (curves *3*, *4*). Here, for weld pool volume (up to 8–10 cm^3), changes of $C(t)$, depending on (1), differ considerably from those given in [5]. However, for the pool specified in this work of up to 40–50 cm^3 volume that forms during the process of electroslag remelting, the results of both the calculations coincide.

Results of investigations using the model considered in this paper at different variants of the laws of the volume feed rate change of alloying electrode and their comparison with the results of the experiment, lead to the conclusion of the model adequacy and its applicability for prediction of weld chemical composition. This enables real-time control of the alloying process, as the signal on the winding of electrode feed motor is used as the input parameter. Modeling also showed that the overalloying effect can be used in order to increase the alloying level or shorten the time of transition [6, 7]. For this purpose, the law of the feed rate change during the transition envisages an area in which the maximum

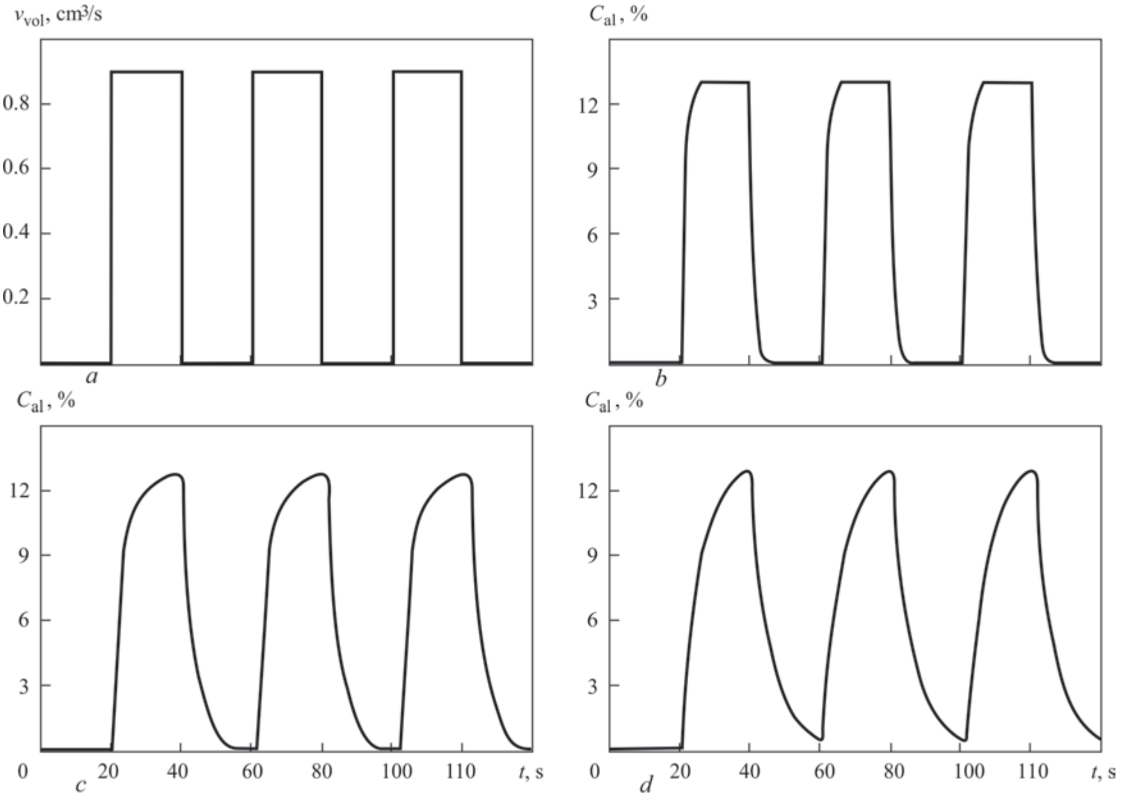

Figure 3. Nature of the change of weld composition $C(t)$ at rectangular shape of alloying electrode feed pulses: *a* — law of the change of $v_{al}(t)$; *b* — $C(t)$ calculation for $V = 1$; *c* — for $V = 3$; *d* — same, for $V = 5$ cm^3

rate is kept constant, or electrodes are used which have a higher content of the alloying element than is required for obtaining the necessary concentration in the weld. However, the need to apply (impossibility to replace) the high-alloyed electrode beyond the overalloying area is accompanied by a significant increase of the expenses, and application of this variant of the technology is economically not feasible under production conditions.

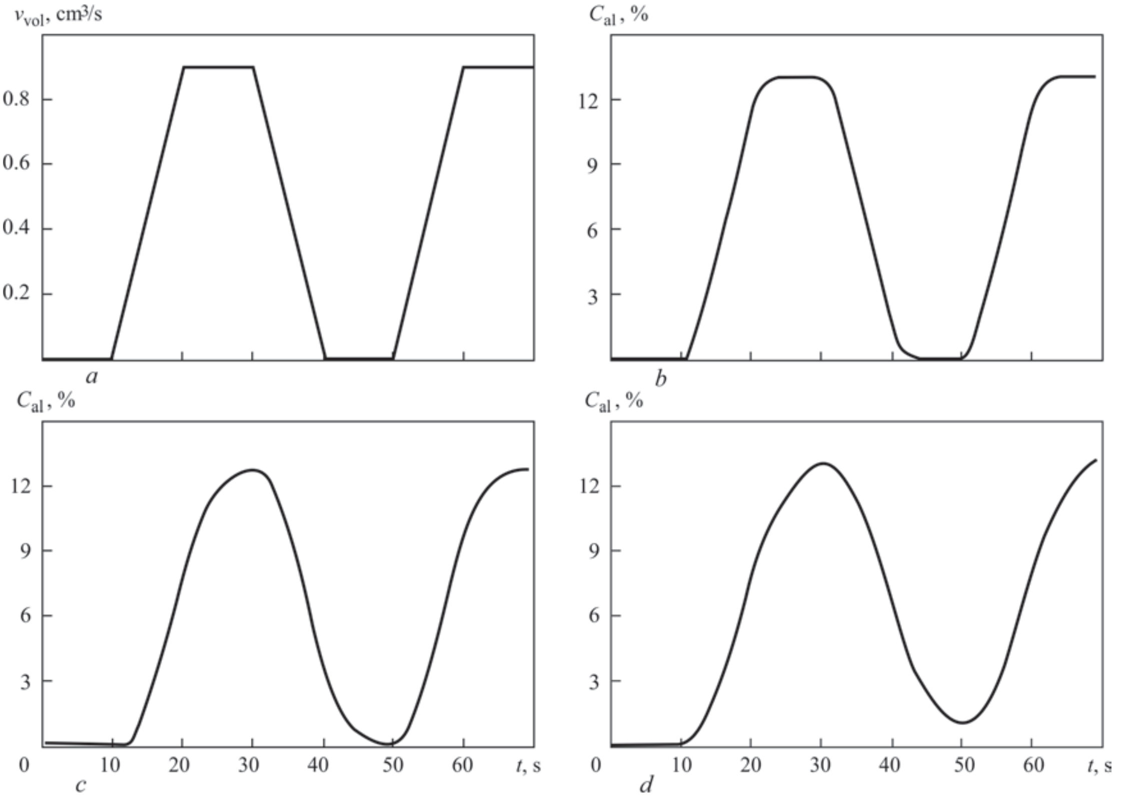

Figure 4. Change of weld composition $C(t)$ at trapezoidal shape of alloying electrode feed pulses: *a* — law of $v_{al}(t)$ change; *b* — $C(t)$ calculation for $V = 1$; *c* — for $V = 3$; *d* — same for $V = 5$ cm^3

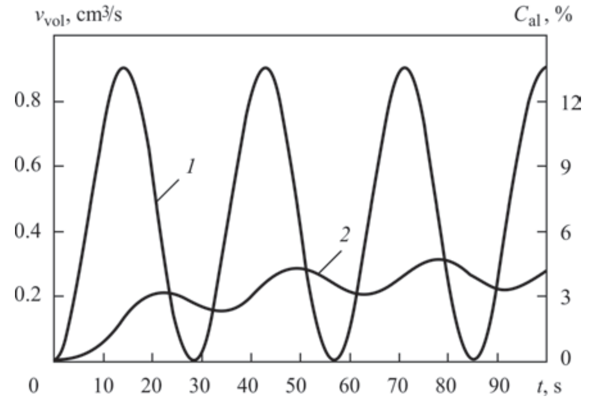

Figure 5. Effect of sinusoidal shape of alloying electrode feed pulses on $C(t)$ change: *1* — law of $v_{al}(t)$ change; *2* — $C(t)$ calculation ($V = 3$ cm^3)

Proceeding from the calculated data, a discrete change of alloying electrode feed rate $v_{al}(t)$ provides a close to jumplike change of the composition $C(t)$ (Figure 3). In practice such a discrete change of the alloying element content in most of the cases is realized using a folded (along the length) electrode. As one can see from Figure 3, in case of a rectangular shape of the feed rate pulse, the high alloying gradient at the initial stage of the rising branch decreases at its final stage right up to smooth change of $C(t)$. The nature of such changes in the descending branch is similar. Modeling revealed that irrespective of weld pool volume and time parameters, at a symmetrical shape of the pulse, the alloying element distribution at the rising stage and concentration lowering are asymmetrical.

Such an asymmetry is manifested to a smaller extent for the trapezoidal shape of the feed pulse, particularly with the reduction of the weld pool volume (Figure 4). At the same time, according to experimental data [6, 7], these areas on the curve of alloying element distribution in the deposited metal differ to a smaller degree. Moreover, changing the slope of the function of alloying electrode feed rate to this or that side, it is possible to ensure the symmetry of the ascending and descending branches of alloying element concentration in the weld [8]. Considering the effect of gradient sign on the shape of the curve of concentration change, characteristic for central and not axial symmetry, the symmetry of the ascending and descending branches of concentration is provided by breaking up the curve of concentration change into sections with different law of alloying electrode feed rate.

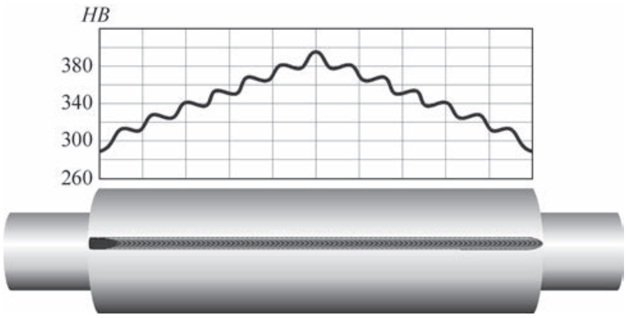

Figure 7. Hardness distribution along the forming roll barrel at formation of the deposited layer from longitudinal welds

As shown by modeling results, in the presence of two sections at the stage of electrode feed rate increase and decrease, the symmetry of the change of weld alloying is ensured, in order to solve a whole range of tasks of investigation and development of technology for deposition of metal having a variable chemical composition.

Change of parameters of the sinusoidal law of volume feed rate of the electrode allows deriving a similar law of alloying element distribution along the weld length (Figure 5). Here, the change of the level of weld metal alloying in the direction of the vector of deposition rate enables obtaining a layer of variable composition and hardness.

Known are the methods and devices that allow realization of the sinusoidal law of the change of electrode wire and strip feed rate [9, 10]. Irrespective of the method of generation of oscillations, the range of parameters used in such devices, allows controlling the characteristics of electrode metal transfer, but does not allow controlling the change of weld chemical composition, because of the inertia of the process of weld pool formation. Deposition of weld areas, differing by their chemical composition, depends on the ability to ensure a periodic change of the rate of feeding electrodes with different degrees of alloying. Here, the duration and relative pulse duration of feed pulses should greatly exceed the time of weld pool existence. In addition, it is necessary to provide the possibility of variation of these parameters in a broad range.

For realization of the task of program control of electrode feed rate, a circuit of controlling the DC commutator motors of SL type was developed on the base of a programmable microcontroller ATmega328P (Figure 6). Controller programming and system operation

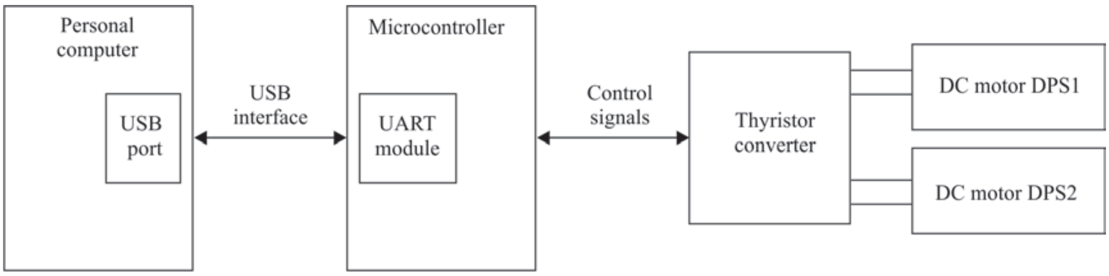

Figure 6. Structural scheme of the control system of electrode feed motors

Composition and hardness of the deposited layer along the roll length

Chromium content and hardness	Area location on roll barrel		
	on barrel edge	at the distance of 1/4 of the length from the edge	in the middle of the barrel
Chromium content, wt.%	1.12	6.2	12.6
Hardness, *HB*[*] at *T* = 430 °C	$\frac{340}{290}$	$\frac{410}{340}$	$\frac{450}{390}$

[*]Numerator — after deposition, denominator — after tempering.

control are performed with application of a personal computer connected via a built-in interface converter USB-UART (Universal Asynchronous Receiver-Transmitter). A standard thyristor converter was used to form pulses of current for control of drives for feeding electrodes with different content of alloying elements. AC supply voltage of the circuit is rectified and modulated by PWM signals, coming to the thyristor control pin from the controller discrete output. This allows ensuring control of electrode feed rate, in keeping with the dependencies given in the graphs (Figures 3–5). Here, the duration of individual sections is comparable with the time of weld pool existence.

Proceeding from results of modeling the processes of deposition of a layer of variable chemical composition, a technology was developed for reconditioning of working rolls of crimp stand of a continuous billet rolling mill (roll material is 50KhN steel, barrel diameter is 600 mm, barrel length is 1000 mm). It is known that cracking under the impact of thermal fatigue and impact loading, associated with formation of circumferential cracks that go deeply into the roll body, becomes much more pronounced when making the surface layer from circumferential welds [11]. Therefore, the deposited layer was formed from welds, oriented along the forming barrel [12] that allowed increasing the resistance to formation of circumferential cracks in the surface layer of hot roll under the impact of thermal cycles. At application of electrode strip of 40×0.65 mm cross-section (alloyed electrode of Sv-2Kh13, and low-alloyed electrode of 30KhGSA composition) a weld of variable composition, deposited along the roll forming barrel, is characterized by a change of chromium content from 1.12 to 12.6 %. Here, the deposited layer hardness after tempering rises from *HB* 290 to *HB* 390, respectively (Table).

The sinusoidal shape of alloying electrode feed pulses allows achieving the shown in Figure 7 nature of hardness variation — from the minimum value on the edges up to maximum value in the barrel middle part, that greatly reduces the nonuniformity of wear of working rolls of the crimp stand in continuous billet rolling mill.

Conclusions

1. Mathematical modeling of the technology for deposition of welds of variable chemical composition allows prediction of the change of alloying element content in the area of transition, depending on alloying electrode feed rate and weld pool volume. The model adequacy is confirmed by experimental results.

2. Modeling revealed that weld composition change close to the discrete one, can be achieved in the case of application of the law of alloying electrode feeding in the form of pulses of a trapezoidal shape. The asymmetry of the thus obtained areas of increase and decrease of alloying element concentration in the weld is manifested to a smaller degree with reduction of weld pool volume.

3. Modeling was the base for development of the technology of strengthening the forming rolls with formation of the deposited layer from the welds located along the barrel, and having the composition and hardness variable along their length, by changing the volume rate of alloying electrode feeding in the form of pulses of a sinusoidal shape.

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