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MATHEMATICAL MODELLING OF FLUX-CORED LAYER FORMATION

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Abstract: Mathematical model for the calculation of the chemical composition of deposited metal with sufficient accuracy has been developed. The presented mathematical model has been developed taking into account shares of base and clad metal, the metal of the previous roll in the subsequent one, and the relative step of cladding. Based on the calculated composition of deposited metal by flux-cored wire it has been proved and experimentally confirmed that the required chemical composition of deposited metal is achieved in the second-third layer regardless of the surfacing step. Theoretically established and experimentally verified the effective relative step of cladding. The established relative pitch allows for minimizing waste when cladding with flux-cored wire. In this case, the cross-sectional area of the roll reinforcement after the finishing run will be minimal.

Keywords: electric arc cladding, weld metal, flux-cored wire, mathematical modeling, chemical composition.

Introduction

Hardfacing with powder electrodes (strips, wires) is one of the most effective resource-saving methods of hardening with the application of special alloys [1–4]. Such alloys possess high wear resistance and ensure the long-term preservation of the optimum geometry of the working body. Satisfaction with regulations of operational reliability of deposited metal, the ability to withstand various types of wear, compliance with the principles of interchangeability, and economic feasibility are largely determined by the quality of the flux-cored electrode and the metal deposited by it. Of the known and widely used methods of wear-resistant (complexly alloyed and composite) alloying the most universal is mechanized open arc cladding with powder electrodes [1–6]. The efficiency of using flux-cored electrodes for large volumes of surfacing decreases, because the productivity of surfacing does not meet the high energy costs of the electrode melting process. In addition, there is insufficient information about the development of reliable computer systems for calculating the surfacing process's technological parameters, considering the deposited metal's necessary chemical composition, the size of parts, and the minimum allowance for subsequent machining [6, 7].

In this regard, conducting complex theoretical and experimental research aimed at maximum refinement of initial data, development of prediction methods, calculation, process optimization, and mathematical models, represents an urgent task. Such developments will contribute to the development of recognized advances in the field of cladding with powder electrodes of wear-resistant alloys, which is of important scientific and practical importance.

Literature analysis

Obtaining a quality clad layer with the required chemical composition is the main task of hardening operations. Therefore, the improvement of surfacing technology and optimization of modes is a relevant area for research. The melting behavior of the flux-cored electrode has a decisive influence on the clad metal's performance characteristics and the process's technological parameters. The melting character of the powder electrode and the qualitative characteristics of the build-up layer (composite or complexly alloyed) is determined by the ratio of sheath and core melting rates, which is determined by the thermal state of the system "sheath-core" [4–7]. The main directions for improvement of surfacing technologies of composite and complexly alloyed alloys with powder electrodes of parts working in different wear conditions are the use of new highly effective technical solutions and optimization of technological regimes. Such solutions are aimed at improving the quality of the powder electrode, the quality and economy of the deposited metal, and the productivity of the process [5–10]. This requires the development of appropriate calculation methods. Their structure and the logic and functional relationships should consider the regularities of imparting the required properties to the built-up surface. Multivariate tasks of investigation of powder electrode fabrication, their heating and melting, and shaping of deposited metal make it expedient to use methods of mathematical modeling to obtain the required volumes of information in real-time [11]. Increased requirements for the volume and degree of reliability of the results of mathematical modeling of these processes require the specification of initial assumptions and boundary conditions in their deterministic and probabilistic aspects.

Purpose of work and problem statement

The work aims to calculate the composition of metal deposited by flux-cored wire.

The following tasks are set to achieve the above objective:

1. To calculate the composition of metal deposited by flux-cored wire, taking into account the shares of the main and deposited metal.
2. To calculate the minimization of metal waste during flux-cored wire surfacing.

Calculation of the composition of the metal deposited by the flux-cored wire

When surfacing a small number of layers to calculate the content of the element Me_n in the n-th layer of cladding, it is necessary to know its concentration in the base metal Me_O and the surfaced metal Me_H, as well as the proportion of the base metal in the metal of the second and subsequent rolls and the proportion of the metal of the previous roll in the subsequent [12]. So, the concentration of the element in the n-th layer of the cladding can be determined by the formula:

$$Me^n = Me_H - (Me_H - Me_O) \cdot \left(\frac{\phi}{1-\delta}\right)^n. \tag{1}$$

Taking the shape of the reinforcement cross-section of the welded roll as a parabola and the shape of the penetration cross-section of the base metal as a semi-ellipse, it is found that the proportion of the base metal in the metal of the second and subsequent rolls can be found by the formula:

$$\phi = \frac{\arcsin\alpha + \alpha\sqrt{1-\alpha^2}}{\frac{4}{3}\beta + \frac{\pi}{2}}. \tag{2}$$

The metal share of the previous roll in the subsequent roll is according to the formula:

$$\delta = \frac{\frac{\pi}{4} + \frac{2}{3}\beta - \beta\left(\alpha - \frac{\alpha^3}{3}\right) - \frac{1}{2}\arcsin\alpha - \frac{1}{2}\alpha\sqrt{1-\alpha^2}}{\frac{\pi}{4} + \frac{2}{3}\beta}, \tag{3}$$

where α – is the relative step of the cladding; β – is the reinforcement factor, equal to the ratio of the height of the weld reinforcement and the depth of penetration.

However, the accepted shape of the reinforcement cross-section of the weld bead in the form of a parabola is typical for flux-cored wire surfacing at currents up to 250 A. For flux-cored welding at high currents (up to 400 A), the shape of the bead cross-section is more accurately described by a semi-ellipse.

For this case it is obtained:

$$\delta = \frac{2}{\pi}(1-\alpha)\sqrt{1-\alpha^2}. \quad (4)$$

However, simplifications were made in the derivation of dependence (4). In particular, the area of the geometric figure AMBC (Fig. 1) was taken as equal to the area of the quadrilateral AMBC. This leads to errors in the calculation of surfacing metal composition. Accurate dependences of and values were found [12] in the case of the shape of the cross-section reinforcement of the cladding roll and penetration of the base metal in the form of semi-ellipses (Fig. 1).

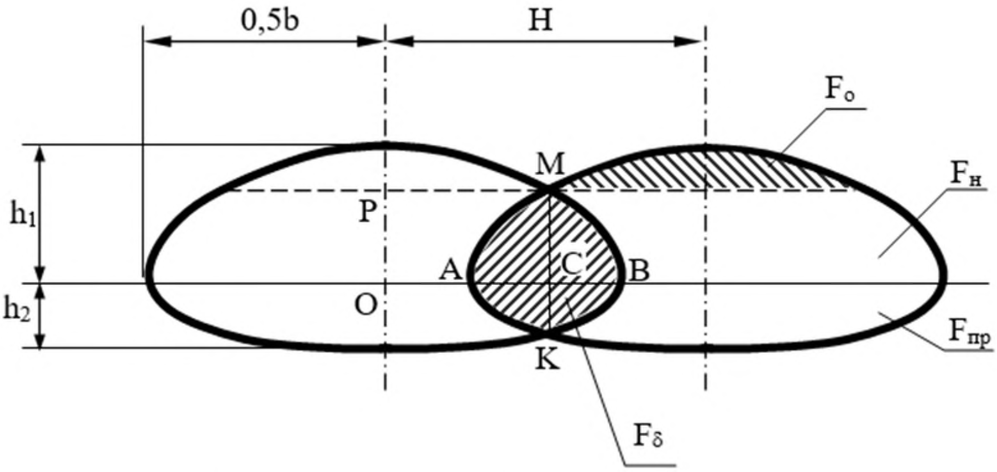

Fig. 1. Calculation of coefficients δ, φ, γ for flux-cored wire cladding

Indeed, in this case, the equation of the ellipse with semi-axes *b/2* and h_1 is as follows:

$$\frac{x^2}{\left(\frac{b}{2}\right)^2} + \frac{y^2}{h_1^2} = 1.$$

From where we find:

$$y = \frac{2h_1}{b}\sqrt{\left(\frac{b}{2}\right)^2 - x^2}. \quad (5)$$

Then the cross-sectional area of the cladding roll:

$$F_H = 2\int_0^{b/2} y dx = \frac{4h_1}{b}\int_0^{b/2}\sqrt{\left(\frac{b}{2}\right)^2 - x^2 dx} = \frac{4h_1}{b}\left(\frac{b^2}{8}\arcsin\frac{2x}{b} + \frac{x}{2}\sqrt{\left(\frac{b}{2}\right)^2 - x^2}\right)\Bigg|_0^{b/2} =$$

$$= \frac{4h_1}{b}\cdot\frac{b^2}{8}\cdot\frac{\pi}{2} = \frac{\pi}{4}h_1 b.$$

The cross-sectional area of the base metal:

$$F_{пр} = 2\int_0^{b/2} y dx = \frac{4h_2}{b}\int_0^{b/2}\sqrt{\left(\frac{b}{2}\right)^2 - x^2 dx} = \frac{4h_2}{b}\left(\frac{b^2}{8}\arcsin\frac{2x}{b} + \frac{x}{2}\sqrt{\left(\frac{b}{2}\right)^2 - x^2}\right)\Bigg|_0^{b/2} =$$

$$= \frac{4h_2}{b}\cdot\frac{b^2}{8}\cdot\frac{\pi}{2} = \frac{\pi}{4}h_2 b.$$

In summary, the cross-sectional area of the clad metal layer:

$$F = F_H + F_{\text{пр}} = \frac{\pi b}{4}(h_1 + h_2). \tag{6}$$

Find the area of the curvilinear triangle AMB. From Fig. 1 we have:

$$F_{AMB} = 2\int_{H/2}^{b/2} \frac{2h_1}{b}\sqrt{\left(\frac{b}{2}\right)^2 - x^2 dx} = \frac{4h_1}{b}\left(\frac{b^2}{8}\arcsin\frac{2x}{b} + \frac{x}{2}\sqrt{\left(\frac{b}{2}\right)^2 - x^2}\right)\Bigg|_{H/2}^{b/2} =$$

$$= \frac{4h_1}{b}\left(\frac{b^2}{8}arcsin\frac{2b}{2b} + \frac{b}{4}\sqrt{\frac{b^2}{4} - \frac{b^2}{4}}\right) - \frac{4h_1}{b}\left(\frac{b^2}{8}\arcsin\frac{2H}{2b} + \frac{H}{4}\sqrt{\frac{b^2}{4} - \frac{H^2}{4}}\right) =$$

$$= \frac{4h_1}{b}\cdot\frac{b^2}{8}\cdot\frac{\pi}{2} - \frac{4h_1}{b}\left(\frac{b^2}{8}\arcsin\frac{H}{b} + \frac{H}{8}\sqrt{b^2 - H^2}\right) = \frac{\pi h_1 b}{4} - \frac{h_1 b}{2}\arcsin\frac{H}{b} -$$

$$-\frac{h_1 H}{2}\sqrt{1 - \left(\frac{H}{b}\right)^2} = \frac{h_1 b}{2}\left(\frac{\pi}{2} - \arcsin\frac{H}{b} - \frac{H}{b}\sqrt{1 - \left(\frac{H}{B}\right)^2}\right).$$

The area of a curvilinear triangle AKB:

$$F_{AKB} = 2\int_{H/2}^{b/2} \frac{2h_2}{b}\sqrt{\left(\frac{b}{2}\right)^2 - x^2 dx} = \frac{4h_2}{b}\left(\frac{b^2}{8}\arcsin\frac{2x}{b} + \frac{x}{2}\sqrt{\left(\frac{b}{2}\right)^2 - x^2}\right)\Bigg|_{H/2}^{b/2} =$$

$$= \frac{4h_2}{b}\left(\frac{b^2}{8}\arcsin\frac{2b}{2b} + \frac{b}{4}\sqrt{\frac{b^2}{4} - \frac{b^2}{4}}\right) - \frac{4h_2}{b}\left(\frac{b^2}{8}\arcsin\frac{2H}{2b} + \frac{H}{4}\sqrt{\frac{b^2}{4} - \frac{H^2}{4}}\right) =$$

$$= \frac{4h_2}{b}\cdot\frac{b^2}{8}\cdot\frac{\pi}{2} - \frac{4h_2}{b}\left(\frac{b^2}{8}\arcsin\frac{H}{b} + \frac{H}{8}\sqrt{b^2 - H^2}\right) = \frac{\pi h_2 b}{4} - \frac{h_2 b}{2}\arcsin\frac{H}{b} -$$

$$-\frac{h_2 H}{2}\sqrt{1 - \left(\frac{H}{b}\right)^2} = \frac{h_2 b}{2}\left(\frac{\pi}{2} - \arcsin\frac{H}{b} - \frac{H}{b}\sqrt{1 - \left(\frac{H}{B}\right)^2}\right).$$

Then the area of the curved quadrilateral AMBK is:

$$F_\delta = \frac{b}{2}(h_1 + h_2)\left(\frac{\pi}{2} - \arcsin\frac{H}{b} - \frac{H}{b}\sqrt{1 - \left(\frac{H}{b}\right)^2}\right). \tag{7}$$

By denoting the relative pitch *H/b* through α, we obtain an expression for the proportion of the metal of the previous roll in the subsequent one:

$$\delta = \frac{F_\delta}{F} = \frac{\frac{b}{2}\left(\frac{\pi}{2} - \arcsin\alpha - \alpha\sqrt{1-\alpha^2}\right)}{\pi b/4} = 1 - \frac{2}{\pi}\left(\arcsin\alpha + \alpha\sqrt{1-\alpha^2}\right). \tag{8}$$

Therefore, the share of metal from the previous roll in the subsequent δ depends only on the relative step of the surfacing α.

Table 1 presents comparative values of parameters δ, calculated by the formula (4) and (8). It can be seen that formula (4) in comparison with formula (8) at a relative step of surfacing = 0.5–0.9 gives an error of 42–25 %.

The fraction of the base metal in the metal of the second and subsequent rolls is determined from the formula:

$$\phi = \frac{F_{\text{пр}} - F_{AKB}}{F} = \frac{\frac{\pi}{4}h_2 b - \frac{h_2 b}{2}\left(\frac{\pi}{2} - \arcsin\alpha - \alpha\sqrt{1-\alpha^2}\right)}{\frac{\pi b}{4}(h_1 + h_2)} = \frac{2h_2\left(\arcsin\alpha + \alpha\sqrt{1-\alpha^2}\right)}{\pi(h_1 + h_2)}.$$

The proportion of the base metal in the metal of the second and subsequent rolls can be determined from the formula:

$$\phi = \frac{F_{\text{пр}} - F_{AKB}}{F} = \frac{\frac{\pi}{4}h_2 b - \frac{h_2 b}{2}\left(\frac{\pi}{2} - \arcsin\alpha - \alpha\sqrt{1-\alpha^2}\right)}{\frac{\pi b}{4}(h_1 + h_2)} = \frac{2h_2\left(\arcsin\alpha + \alpha\sqrt{1-\alpha^2}\right)}{\pi(h_1 + h_2)}.$$

Table 1

Calculation error δ by formula (4) compared to the calculation by formula (8)

α	Calculation δ by formula		Uncertainty. %
	(4)	(8)	
0.5	0.276	0.393	42
0.6	0.204	0.281	38
0.7	0.136	0.187	37
0.8	0.076	0.102	34
0.9	0.028	0.035	25

By dividing the numerator and denominator by h_2 and introducing the amplification factor $\beta = h_1/h_2$, we finally get

$$\varphi = \frac{2\left(arcsin\,\alpha + \alpha\sqrt{1-\alpha^2}\right)}{\pi(1+\beta)}. \tag{9}$$

The values of the coefficient φ for a variation of α between 0.5–0.9 and β between 1.0–3.0 are given in Table 2

Table 2

Coefficient φ_1 value for changes α and β

α	Value φ at β. equal:		
	1	2	3
0.5	0.304	0.202	0.152
0.6	0.356	0.238	0.178
0.7	0.406	0.271	0.204
0.8	0.448	0.299	0.224
0.9	0.482	0.328	0.241

When cladding with a flux-cored electrode it is necessary to ensure a given chemical composition Me_H of the top layer

If we denote by the relative deviation of the concentration of an alloying element in the *n*-layer from its content in the weld metal by:

$$\Delta = \frac{|Me^n - Me_H|}{Me_H} \cdot 100\,\%,$$

from formula (1) we can determine that

$$\frac{\Delta}{100} = \left(1 - \frac{Me_O}{Me_H}\right) \cdot \left(\frac{\phi}{1-\delta}\right)^n. \tag{10}$$

A given alloy composition of the weld metal *Me* can then be obtained in the nth layer, where *n* is calculated by the following formula:

$$n = \frac{ln(\Delta/100) - ln(1 - Me_O/Me_H)}{ln\,\phi - ln(1-\delta)}. \qquad (11)$$

The resulting number must be rounded upwards to a whole number.

Since in the case in question the value of the ratio is $\frac{\phi}{1-\delta} = \frac{1}{1+\beta}$, assuming that $Me_O = 0$, we obtain

$$n = \frac{ln(\Delta/100)}{-\,ln(1+\beta)}. \qquad (12)$$

If Δ=10 %, calculation by formula (12) for β= 1; 2; 3 gives appropriate values *n* = 3.32; 2.10; 1.66, that is, with an accuracy of 10 % the required chemical composition of deposited metal is achieved in the second-third layer of cladding regardless of the step α. Table 3 shows the composition of the deposited layers when cladding steel 45 with step α = 0.7 using a flux-cored wire.

Table 3

The dependence of the composition of metal clad with flux-cored wire, depending on the number of layers

Layer number	Chemical composition of the weld layer, %							
	C	*Mn*	*Si*	*Cr*	*V*	*Mo*	*W*	*Ti*
1	1.48/1.32	2.43/2.64	0.40/0.38	6.33/5.43	1.07/1.12	0.93/0.72	1.00/0.86	0.10/0.60
2	1.83/1.89	3.14/2.96	0.51/0.44	8.44/8.36	1.35/1.24	1.24/1.26	1.33/1.36	0.13/0.15
3	1.94/2.12	3.38/3.51	0.53/0.61	9.15/9.28	1.54/1.46	1.35/1.30	1.44/1.35	0.14/0.12
4	1.98/1.92	3.46/3.36	0.54/0.55	9.38/9.25		1.38/1.43	1.48/1.52	0.15/0.18
Metal cladded in copper form	2.00/2.02	3.50/3.48	0.55/0.58	9.50/9.45	1.60/1.63	1.40/1.44	1.50/1.45	0.15/0.19
Remark. Numerator is the calculated value, the denominator is the experimental value.								

The reinforce factor β was determined experimentally during roll surfacing and is approximately equated 1 to 2. From the comparison of calculated and experimental data it is seen that calculation by the above formulas (1), (8), (9), (11) gives good convergence of results, and the chemical composition of the clad metal is achieved in the second-third layer of the cladding.

Minimizing metal waste in flux-cored surfacing

To save on welding consumables and to reduce machining labor costs, it is necessary to designate surfacing modes and their geometry in such a way that after the final turning of the weld metal, the waste is minimal. Let us find the conditions under which the weld metal waste after the final (finishing) flow-through of the weld metal will be minimal, i.e. the cross-sectional area of the roll reinforcement after the finishing flow-through will be minimal. From equation (5) let us find the length of MC segment, which will be the thickness of the weld metal after the counterbore (see Fig. 1).

We have:

$$MC = \frac{2h_1}{b}\sqrt{\left(\frac{b}{2}\right)^2 - \left(\frac{H}{2}\right)^2} = \frac{2h_1}{2b}\sqrt{b^2 - (\alpha b)^2} = h_1\sqrt{1-\alpha^2}. \qquad (13)$$

Then the reinforcement area of the roll after the counterbore will be equal:

$$F_M = 2F_{OPMC} = H \cdot MC = h_1 b\alpha\sqrt{1-\alpha^2}. \tag{14}$$

Find the maximum area of F_M. To do this, find the derivative of the function (14) by α and equate it to zero.

We obtain:

$$\left(\alpha\sqrt{1-\alpha^2}\right)' = \frac{1-2\alpha^2}{\sqrt{1-\alpha^2}} = 0.$$

then $1 - 2\alpha^2 = 0$. From where:

$$\alpha = \sqrt{0{,}5} \approx 0{,}7. \tag{15}$$

Finally, to obtain minimum waste of deposited metal after a finish facing, surfacing should be carried out with a relative pitch of α = 0.7. At the optimum value of α, the thickness of the deposited layer after roughing will be $0.7h_1$.

Fig. 2 shows a graph of the dependence of the cross-sectional area of the roll reinforcement after a finishing bore FM on the relative pitch α. It can be seen that indeed the maximum F_M area is reached at α = 0.7.

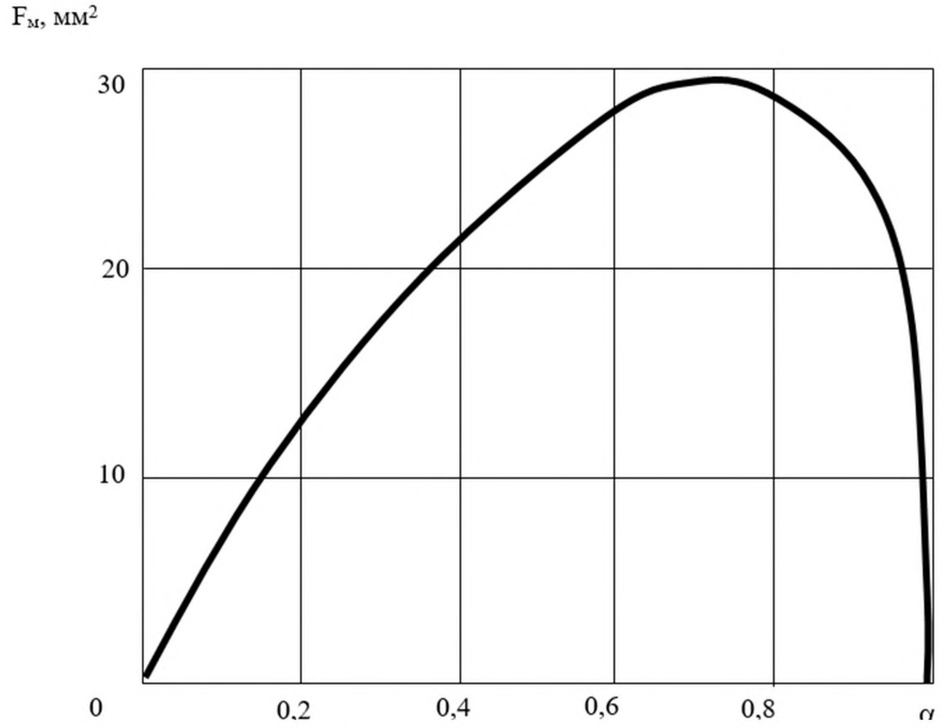

Fig. 2. Dependence of area *Fm* on the relative cladding pitch (h_1 = 4 mm, b = 15 mm)

Let's find the waste area of the welded roll after the groove. We have (see Fig. 1):

$$\begin{aligned} F_0 &= 2\int_0^{H/2}(y - MC)dx = \frac{4h_1}{b}\int_0^{H/2}\sqrt{\left(\frac{b}{2}\right)^2 - x^2}dx - 2\int_0^{H/2} h_1\sqrt{1-\alpha^2}dx = \\ &= \frac{4h_1}{b}\left(\frac{b^2}{8}\arcsin\frac{2x}{b} + \frac{x}{2}\sqrt{\left(\frac{b}{2}\right)^2 - x^2}\right)\Bigg|_0^{H/2} - 2h_1\sqrt{1-\alpha^2}x\Bigg|_0^{H/2} = \\ &= \frac{4h_1}{b}\left(\frac{b^2}{8}\arcsin\frac{2H}{2b} + \frac{H}{4}\sqrt{\left(\frac{b}{2}\right)^2 - \left(\frac{H}{2}\right)^2}\right) - h_1H\sqrt{1-\alpha^2} = \\ &= \frac{h_1 b}{2}\arcsin\alpha + \frac{h_1 H}{2}\sqrt{1-\alpha^2} - h_1H\sqrt{1-\alpha^2} = \frac{h_1 b}{2}\left(\arcsin\alpha - \alpha\sqrt{1-\alpha^2}\right). \end{aligned} \tag{16}$$

Then the proportion of the remaining metal after the groove γ can be found from:

$$\gamma = \frac{F_M}{F_M + F_O} = \frac{2\alpha\sqrt{1-\alpha^2}}{\arcsin\alpha + \alpha\sqrt{1-\alpha^2}}. \quad (17)$$

Fig. 3 shows a graph of the proportion of metal remaining after bore γ as a function of the relative pitch α. The graphical dependencies show that, in order to obtain minimal waste of deposited metal after sheet surfacing, flux-cored wire should be deposited at a relative pitch of α =0.7. In this case, the proportion of remaining metal after machining will be 78 %.

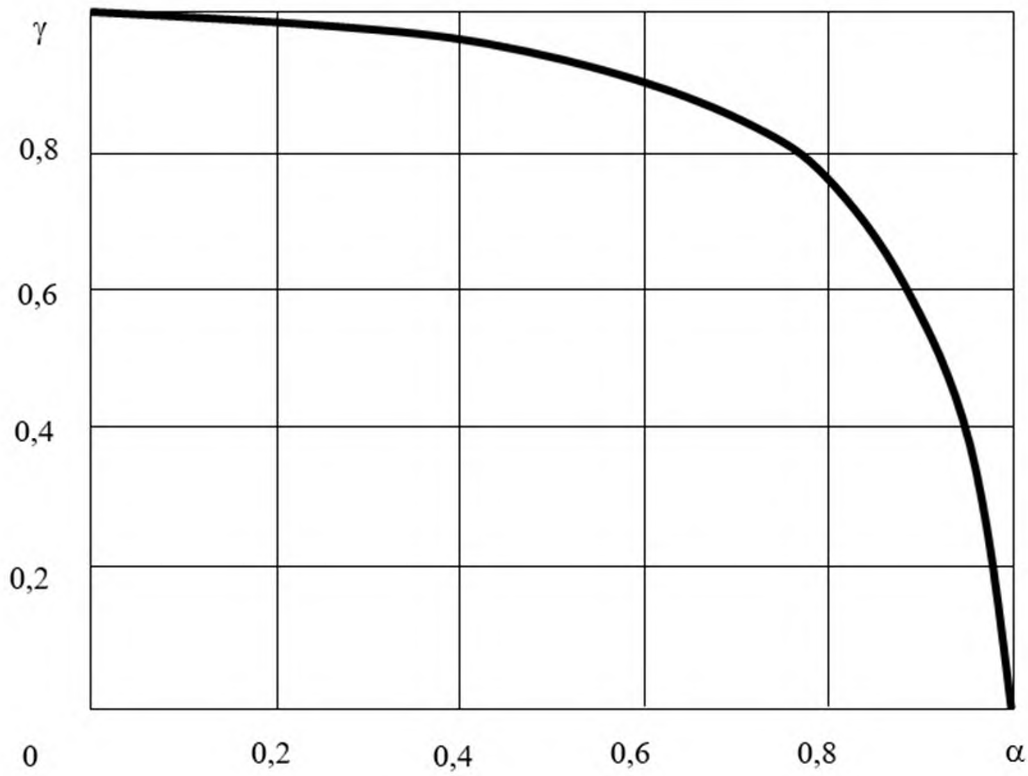

Fig. 3. Dependence of the proportion of metal remaining after bore γ on the relative pitch α

Conclusions

A mathematical model of the formation of the layer deposited by flux-cored wire has been developed. Expressions for calculating with sufficient accuracy the chemical composition of the deposited layer taking into account the share of the base mtal φ, the metal of the previous roll in the subs ent δ and the relative pitch α for different modes of surfacing have been obtained. It has been theoretically proved and experimentally verified that the required chemical composition of the deposited metal is achieved in the second-third layer regardless of surfacing step α.

It has been established that to obtain minimum waste of deposited metal after sheet surfacing it is necessary to deposit flux-cored wire with relative pitch α = 0.7. In this case, the proportion of remaining metal after machining will be 78 %.

References

[1] Buntoeng Srikarun, Hein Zaw Oo, Prapas Muangjunburee Influence of Different Welding Processes on Microstructure, Hardness, and Wear Behavior of Martensitic Hardfaced Cladding [Journal of Materials Engineering and Performance]. 2021 (30), pp. 8984–8995. https://doi.org/10.1007/s11665-021-06109-0.

[2] Venkatesh B. *Mechanical Behavior of Single and Multilayer Hardfacing on Ferrous Alloys [Tribology and Characterization of Surface Coatings]*. 2022. https://doi.org/10.1002/9781119818878.ch13

[3] Dmitry A. Chinakhov, Kirill O. Akimov *Formation of the Structure and Properties of Deposited Multilayer Specimens from Austenitic Steel under Various Heat Removal Conditions [Metals].* 12(9), 1527; https://doi.org/10.3390/met1209152.

[4] João V. S. Matias, Manuel J. C. Lourenço, Jorge C. F. Jorge *Behavior of a superaustenitic stainless steel weld cladding deposited by the gas metal arc welding process [Materials Today Communications].* 2022. https://doi.org/10.1016/j.mtcomm.2022.104978.

[12] Najafi M., Moshkbar M. Bakhshayesh, Farzadi A. *Microstructure and Phase Analysis of Multilayer Ni–Cr–Mo Clad for Corrosion Protection [Transactions of the Indian Institute of Metals].* 2021 (74), pp. 1663–1672. https://doi.org/10.1007/s12666-021-02256-z.

[6] Sokolov G. N., Zorin I. V., Artem'ev A. A., Elsukov S. K., Dubtsov Yu. N., Lysak V. I. *Thermal- and wear-resistant alloy arc welding depositions using composite and flux-cored wires with TiN, TiCN, and WC nanoparticles [Journal of Materials Processing Technology].* 2019, pp. 100–110. https://doi.org/10.1016/j.jmatprotec.2019.05.014.

[7] Michael P. Shalimov, Votinova E. B. *Appication of the Complete Material Balance Method to Estimate the Transition of Elements in Flux Cored Arc Welding [Solid State Phenomena].* 2020, pp. 559–564. https://www.scientific.net/SSP.299.559.

[8] Jingli Zhang, Jianjun Wei *Effect of interlayer temperature and extremely low terminal cooling temperature on the microstructure and wear resistance of Fe-based hardfacing alloy [Journal of Materials Research and Technology].* 2023. https://doi.org/10.1016/j.jmrt.2023.02.012.

[9] Vitaliy Ivanov, Elena Lavrova *Improving the Efficiency of Strip Cladding by the Control of Electrode Metal Transfer [Applied Mechanics and Materials].* 2014, pp. 266–269. https://doi.org/10.4028/www.scientific.net/AMM.682.266.

[10] Weingrill L., Nasiri M. B., Enzinger N. *Thermo-metallurgically coupled numerical simulation and validation of multi-layer gas metal arc welding of high strength pearlitic rails [Welding in the World].* 2019 (63), pp. 63–73. https://link.springer.com/article/10.1007/s40194-018-0639-x.

[11] Fengjing Xu, Runquan Xiao, Zhen Hou, Yanling Xu, Huajun Zhang, Shanben Chen *Multi-layer Multi-pass Welding of Medium Thickness Plate: Technologies, Advances and Future Prospects [Transactions on Intelligent Welding Manufacturing].* 2021. https://link.springer.com/chapter/10.1007/978-981-33-6502-5_1.

[12] Kassov V., Razumovich O. *Mathematical simulation of the metal deposited cored wire complex design [Bulletin of Kharkiv National Automobile and Highway University].* 2014 (65–66). pp. 131–134.