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DETERMINING FORMATION FEATURES OF A WEAR-RESISTANT LAYER SURFACED WITH POWDER TAPE

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This study investigates the technological process of surfacing parts with a powder tape. The task addressed is to optimize the technological process of multilayer arc surfacing with powder tapes based on mathematical modeling of the formation of a seam of a given chemical composition with a minimum allowance for subsequent mechanical processing.

The technological parameters for the coating formation process have been calculated depending on the thickness of the surfacing layer of surfaces after machining, the maximum number of surfacing layers, and the required chemical composition of the weld metal. That has made it possible to devise technological recommendations for surfacing complex alloys on parts of a wide range of applications that operate under conditions of intensive wear.

The results are relevant in additive technologies, part of which is arc surfacing with powder electrodes of various designs, when it is necessary to fabricate an article by sequentially applying layers along a trajectory that repeats the geometry of the parts. The proposed mathematical models make it possible to obtain a reliable and operational assessment of the influence of technological process parameters on the formation of the chemical composition and geometry of the deposited layer during multilayer surfacing, taking into account the minimum waste of deposited metal after finishing grooving.

With values of the ratio of the height of the reinforcement roller to its width (≤ 0.3) and the relative surfacing step within 0.75–0.90, the maximum efficiency of the formation of a multilayer coating is ensured (by the minimum height of the deposited layer). It also enables the minimization of costs for subsequent machining, taking into account the imitation of errors (by the maximum height of irregularities). If the weld reinforcement coefficient is more than 2, then the required chemical composition is achieved already in the second coating layer.

The resulting numerical accuracy makes it possible to predict effective ways to save welding materials and reduce the labor intensity of the process when surfacing complex-alloyed wear-resistant alloys

Keywords: powder tape, multilayer deposition, deposited metal, mathematical model, complex alloys

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1. Introduction

Given the task to improve the efficiency of restoring worn-out components and equipment parts by growing them to rated sizes, arc surfacing with powder tapes has been successfully used [1, 2]. The number of parts that are subject to restorative surfacing to compensate for wear and have a sufficient resource of durability and strength is quite large, as is their range [3]. They have different service characteristics and, accordingly, different chemical composition of the deposited metal. Obtaining a surfacing metal of a given composition is a mandatory condition for the arc surfacing technological process [4]. In addition, in order to save welding materials and reduce the labor intensity of machining, surfacing modes and its geometry should be assigned in such a way that after the final grooving of the surfacing part, the waste of the surfacing metal is minimal. Since when surfacing high-alloy alloys, subsequent machining is associated with a high degree of wear of the processing metal-cutting tool, surfacing with minimal waste of surfacing metal gives the best formation of the surfacing layer. This is due to the fact that each subsequent layer of a multilayer surfacing is applied to the flat surface of the previous layer.

In this regard, studies aimed at optimizing surfacing with a powder tape based on establishing the relationship between the chemical composition of the surfacing layer and the technological features of the process are relevant.

2. Literature review and problem statement

In [5], the technological features of powder tape production by fixing and compacting the charge alloying filler in a metal shell are described. The filler compositions are multicomponent, complex, and represent an optimum that to one degree or another satisfies the set of requirements for materials for surfacing [6]. However, the optimal composition is selected empirically, which complicates the prediction of the quality of the deposited layer. In addition, it is not taken into account that the chemical composition of the deposited layer, in turn, is determined by the composition of the base and filler metals and the proportions of their participation in the deposited layer. During surfacing, the composition of the weld metal and its operational characteristics largely depend on the conditions of heating and melting of the powder tape (shell and filler) [7]. The results make it possible to obtain the required composition of the deposited metal but to save welding materials, it is necessary to take into acco unt the geometry of the deposited layers. When restoring parts with significant surface wear or in the presence of significant defects, there is a need for multilayer surfacing [8]. Modes have been established that affect the penetration depth, weld morphology, and chemical composition of the deposited metal. However, when devising the technology for controlling the geometry of the surfacing rollers, factors that affect the minimization of waste of the surfacing metal were not taken into account. In this case, the chemical composition of the subsequent layers is different. This is due to the fact that with a large number of surfacing layers, the proportion of the base metal decreases until the complete absence of interference of the base metal elements in the composition of the surfacing layer [9]. In this case, each subsequent surfacing layer may differ from the previous one in both chemical composition and mechanical properties.

There are known methodologies for calculating the chemical composition of the deposited metal, taking into account its mixing with the base metal, in relation to specific welding processes [10, 11]. Experimental data obtained for specific conditions of deposition do not make it possible to guarantee the accuracy of the forecast when changing the technological parameters. When studying the influence of the geometry of the deposited layer on the stabilization of its chemical composition, it is assumed that the welding current has the greatest influence on the penetration and the proportion of the base metal in the deposited layer. The voltage on the arc affects the stability of the process, the quality of the formation of the deposited bead. However, when optimizing the technological parameters of multilayer deposition, it is necessary to ensure the required operational properties of the following (working) layers.

In [12], the calculation of the parameters of arc welding with a flux-cored wire is reported in order to optimize the chemical composition of the deposited metal. However, the proposed mathematical model is not universal since it is built on the basis of statistical methods, which reduces its reliability for a wide range of electrode materials. In [13], an algorithm is proposed that is sufficiently accurate to solve the problems of forming the chemical composition and geometric parameters of the layer in the conditions of manual arc welding with covered electrodes. However, under the conditions of wide-layer surfacing, typically under the conditions of surfacing with powder tapes, it is ineffective.

In [14, 15], options for increasing the surfacing productivity by reducing the number of layers are suggested. This relates to the fact that the application of layers that are minimally necessary to compensate for wear and to achieve the required values of accuracy and cleanliness of processing is a priority task. In view of this, the optimization problems of the technological process of multilayer surfacing with powder tapes must be solved on the basis of mathematical modeling of the formation of a seam of a given chemical composition with a minimum allowance for subsequent machining. This is due to the fact that when performing multilayer surfacing, the number of independent factors increases and, as a result, makes statistical methods for planning multifactor experiments ineffective.

In this regard, it is advisable to mathematically model the technological parameters of surfacing that affect the formation of the wear-resistant layer. Such parameters include the surfacing step, the weld reinforcement coefficient, the proportion of the metal of the previous roller in the next, the base metal in the roller metal, and the metal remaining after machining.

3. The aim and objectives of the study

The purpose of our study is to determine the features of the formation of a wear-resistant layer deposited with a powder tape. This will make it possible to solve under industrial conditions the technological tasks of increasing the efficiency of the process and the quality of the deposited metal, as well as the task of ensuring the economy of material resources.

To achieve this goal, the following tasks were set:

– to build a mathematical model for calculating the chemical composition of the metal deposited with a powder tape, taking into account the participation shares of the main and deposited metal, the metal of the previous roller in the next and relative deposition step;

– to construct a mathematical model for the formation of the geometry of a multilayer deposition, taking into account the minimum waste of the deposited metal after the final grooving of the deposited layer.

4. The study materials and methods

The object of our study is the technological process of surfacing parts with a powder tape.

The principal hypothesis assumes that the adequacy of mathematical models of the formation of a layer surfacing with a powder tape is ensured by taking into account the relationship between the technological parameters of the process with the chemical composition in the required layer and the minimum allowance for subsequent machining.

When calculating the composition of the metal surfacing with a powder tape and choosing the surfacing geometry taking into account the minimum waste of surfacing metal after the final grooving of the surfacing layer, the following were adopted (Fig. 1):

– the chemical composition of the layer is formed by mixing the base and surfacing metal, as well as partial remelting of previously formed rollers;

– the shape of the cross-section of the surfacing reinforcement in the form of a rectangle rounded by an arc of a circle of radius h_1;

– the shape of the cross-section of the base metal penetration is in the form of a parabola with an equation of the form

$$y = ax^2 - h_2,$$

where h_2 is the penetration depth; $a = 4 \cdot h_2 / b^2$ from the ratio $a \cdot (b / 2)^2 - h_2 = 0$; b is the width of the surfaced roller.

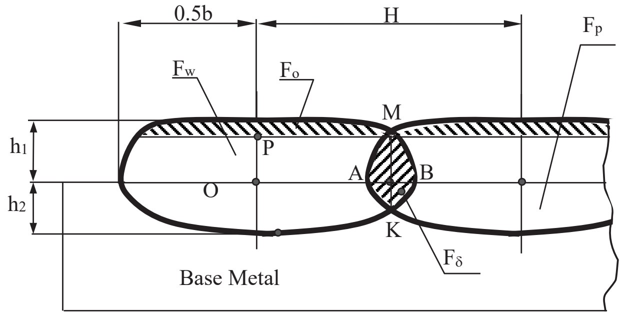

Fig. 1. Calculating the parameters of a roller surfaced with a powder tape: F_w – area of the surfaced roller above the base metal; F_w – area of the melted base metal; F_0 – area of waste of the surfaced roller after grooving; F_δ – area of overlap of the previous roller with the next; h_1 – height of the surfaced layer; h_3 – depth of melting; H – step of surfacing; b – width of the surfaced roller

We studied the features in the formation of a layer surfaced with a powder tape by a mechanized electric arc technique. The ADF-1004 machine was used, and the VDU-1200 was applied as a power source. Several rollers were applied, and then layers of the surfaced metal were applied under the following modes: welding current 650–750 A, arc voltage 30–34 V, electrode extension 50 mm, surfacing speed 32 m/h. The formation of wear-resistant alloys was studied using powder tape electrode materials PL-3X4V3F and PL-5X3V3MFS for surfacing a heavily loaded tool (analogs of the well-known powder tapes of the PL-AN series [16]). The chemical composition of the surfaced metal was determined layer by layer according to the results from Electrone Probe Microanalysis as the average of five measurements within the analyzed area. The preparation of the surfaced samples was carried out by cutting on a UNITOM-2 cutting machine equipped with water cooling of the cutting zone. The geometry was analyzed in terms of the height of the surfaced layer h_1, the penetration depth h_2, the width of the roller b, the penetration step H, and the area of the surfaced roller above the base metal F_w and the area of the penetrated base metal F_p were also determined.

5. Results of research on the formation of a wear-resistant layer surfaced with a powder tape

5. 1. Construction of a mathematical model for calculating the chemical composition of the metal surfaced with a powder tape

To calculate the parameters of a roller surfaced with a powder tape, the cross-sectional area of the surfaced roller should be found (Fig. 1)

$$F_W=\left(b-2\cdot h_1\right)\cdot h_1+\pi\cdot h_1^2/2=$$
$$=b\cdot h_1-h_1^2\cdot\left(2-\frac{\pi}{2}\right)=h_1\cdot\left[b-h_1\cdot\left(2-\frac{\pi}{2}\right)\right], \quad (1)$$

where b is the width of the surfaced roller; h_1 is the height of the surfaced layer.

The cross-sectional shape of the base metal penetration can be described by an equation of the form

$$y=\frac{4\cdot h_2}{b^2}\cdot x^2-h_2, \quad (2)$$

where h_2 is the penetration depth.

The cross-sectional area of the base metal penetration is

$$F_P=\left|2\cdot\int_0^{b/2}y\mathrm{d}x\right|=2\cdot\int_0^{b/2}\left(-\frac{4\cdot h_2}{b^2}\cdot x^2+h_2\right)\mathrm{d}x=$$
$$=2\cdot\left(-\frac{4\cdot h_2}{b^2}\cdot\frac{x^3}{3}+h_2\cdot x\right)\Bigg|_0^{b/2}=$$
$$=2\cdot\left(-\frac{4\cdot h_2}{b^2}\cdot\frac{b^3}{3\cdot 8}+h_2\cdot\frac{b}{2}\right)=-\frac{h_2\cdot b}{3}+h_2\cdot b=\frac{2}{3}\cdot h_2\cdot b. \quad (3)$$

Therefore, the cross-sectional area of the layer is

$$F=F_W+F_P=h_1\left[b-h_1\cdot\left(2-\frac{\pi}{2}\right)\right]+\frac{2}{3}h_2 b=$$
$$=b\left[h_1\cdot\left(1-\frac{0{,}43h_1}{b}\right)+\frac{2}{3}h_2\right], \quad (4)$$

where F_w is the area of the surfaced roller above the base metal; F_p is the area of the melted base metal.

The area of the curvilinear triangle AMB is

$$F_{AMB}=2\cdot\int_{\omega h_1}^{h_1}\sqrt{h_1^2-x^2}\mathrm{d}x=$$
$$=2\cdot\left(\frac{h_1^2}{2}\cdot\arcsin\frac{x}{h_1}+\frac{x}{2}\cdot\sqrt{h_1^2-x^2}\right)\Bigg|_{\omega h_1}^{h_1}=$$
$$=h_1^2\cdot\arcsin\frac{h_1}{h_1}+h_1\cdot\sqrt{h_1^2-h_1^2}-h_1^2\cdot\arcsin\omega-$$
$$-\omega\cdot h_1\cdot\sqrt{h_1^2-\omega^2\cdot h_1^2}=\frac{\pi\cdot h_1^2}{2}-h_1^2\cdot\arcsin\omega-$$
$$-\omega\cdot h_1^2\sqrt{1-\omega^2}=h_1^2\cdot\left(\frac{\pi}{2}-\arcsin\omega-\omega\sqrt{1-\omega^2}\right). \quad (5)$$

The value of ω in expression (5) can be found from the relation (Fig. 1)

$$H/2-(b/2-h_1)=\omega\cdot h_1,$$

then $H-b+2\cdot h_1=2\cdot\omega\cdot h_1$, here H – surfacing step.

Hence

$$\omega=\frac{H-b+2\cdot h_1}{2\cdot h_1}. \quad (6)$$

If $H=b-2h_1$, then $\omega=0$ and the area of triangle AMB reaches its maximum value $\pi\cdot h_1^2/2$. If $H=b$, then $\omega=1$, the area of the triangle AMB is 0, that is, there is no overlap of the rollers.

The area of the curvilinear triangle *AKB* is

$$F_{AKB}=2\cdot\int_{H/2}^{b/2}\left(-\frac{4\cdot h_2}{b^2}\cdot x^2+h_2\right)\mathrm{d}x=$$
$$=2\cdot\left(-\frac{4\cdot h_2}{b^2}\cdot\frac{x^3}{3}+h_2\cdot x\right)\Bigg|_{H/2}^{b/2}=-\frac{8\cdot h_2}{b^2}\cdot\frac{b^3}{3\cdot 8}+$$
$$+2\cdot\frac{h_2\cdot b}{2}+\frac{8\cdot h_2}{b^2}\cdot\frac{H^3}{3\cdot 8}-\frac{2\cdot h_2\cdot H}{2}=$$
$$=-\frac{h_2\cdot b}{3}+h_2\cdot b+\frac{h_2\cdot b}{3}\left(\frac{H}{b}\right)^3-h_2\cdot b\cdot\left(\frac{H}{b}\right)=$$
$$=\frac{2}{3}\cdot h_2\cdot b-h_2\cdot b\cdot\left[\frac{H}{b}-\frac{1}{3}\cdot\left(\frac{H}{b}\right)^3\right]. \quad (7)$$

Then the area of the curved quadrilateral AMVK is

$$F_\delta = h_1^2 \cdot \left(\frac{\pi}{2} - \arcsin\omega - \omega \cdot \sqrt{1-\omega^2} \right) +$$
$$+ h_2 \cdot b \cdot \left[\frac{2}{3} - \frac{H}{b} + \frac{1}{3} \cdot \left(\frac{H}{b} \right)^3 \right].$$

If we denote the relative surfacing step H / b by α, and the value h_1 / b by P, we can obtain

$$F_\delta = h_1 \cdot b \cdot P \cdot \left(\frac{\pi}{2} - \arcsin\omega - \omega \cdot \sqrt{1-\omega^2} \right) +$$
$$+ h_2 \cdot b \cdot \left(\frac{2}{3} - \alpha + \frac{\alpha^3}{3} \right). \quad (8)$$

Thus, the share of the metal of the previous roller in the next one can be calculated from the formula

$$\delta = \frac{F_\delta}{F} = \frac{h_1 \cdot P \cdot \left(\frac{\pi}{2} - \arcsin\omega - \omega\sqrt{1-\omega^2} \right) + h_2 \left(\frac{2}{3} - \alpha + \alpha^3 / 3 \right)}{h_1 (1 - 0.43 \cdot P) + \frac{2}{3} h_2}.$$

When introducing the gain coefficient $\beta = h_1 / h_2$, the proportion of the metal of the previous roller in the next can be expressed as

$$\delta = \frac{\beta \cdot P \cdot \left(\frac{\pi}{2} - \arcsin\omega - \omega\sqrt{1-\omega^2} \right) + 2/3 - \alpha + \alpha^3 / 3}{\beta \cdot (1 - 0.43 \cdot P) + 2/3}. \quad (9)$$

The coefficient ω can be expressed in terms of quantities α and P, then

$$\omega = \frac{b}{2 \cdot h_1} \cdot \left(\frac{H}{b} - 1 + 2 \cdot \frac{h_1}{b} \right) = \frac{\alpha + 2 \cdot P - 1}{2 \cdot P}. \quad (10)$$

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

$$\varphi = \frac{F_P - F_{AKB}}{F} = \frac{h_2 \cdot b \cdot (\alpha - \alpha^3 / 3)}{b \cdot \left[h_1 \cdot (1 - 0.43 \cdot P) + \frac{2}{3} \cdot h_2 \right]} =$$
$$= \frac{\alpha - \alpha^3 / 3}{\frac{2}{3} + \beta \cdot (1 - 0.43 \cdot P)}. \quad (11)$$

When welding with a powder tape, it is necessary to ensure a given chemical composition of the upper layer Me_H.

If we denote the relative deviation of the concentration of the alloying element in the n layer from its content in the surfaced metal by

$$\Delta = \frac{|Me^n - Me_H|}{Me_H} \cdot 100\%, \quad (12)$$

then from formula (12) it can be determined that

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

Then the given composition of the surfaced metal according to the alloying element Me can be obtained in n layer, where n is calculated from the following formula

$$n = \frac{\ln(\Delta / 100) - \ln(1 - Me_O / Me_H)}{\ln\varphi - \ln(1-\delta)}.$$

The resulting value should be rounded up to the next whole number. Since in the case under consideration the value of the ratio is $\varphi / (1-\delta) = 1 / (1+\beta)$, then, assuming that $Me_O = 0$, n can be expressed as follows

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

The required chemical composition of the surfaced metal by the alloying element Me with an error Δ, %, can be obtained in the n-th layer, calculated from the formula

$$n = \frac{\ln(\Delta / 100) - \ln(1 - Me_O / Me_H)}{\ln\varphi - \ln(1-\delta)}. \quad (13)$$

Using our mathematical model, calculations of geometric parameters were carried out, the results of which are given below. Tables 1 and 2 show the values of the coefficients δ and φ when changing parameters α within the range of 0.6–0.9, P within the range of 0.05–0.50, and β within the range of 1.0–3.0. The lower limit of the coefficient P for each α is determined from formula (10) provided that $\omega = 0$.

Table 1

The value of coefficient δ when changing parameters α, P and β

α	P	Value of δ at β, which is equal to:		
		1	2	3
0.6	0.20	0.286	0.307	0.317
	0.30	0.269	0.286	0.294
	0.40	0.257	0.271	0.278
	0.50	0.250	0.262	0.268
0.7	0.15	0.198	0.218	0.227
	0.20	0.187	0.205	0.213
	0.30	0.173	0.187	0.193
	0.40	0.163	0.175	0.181
	0.50	0.158	0.168	0.173
0.8	0.10	0.120	0.136	0.144
	0.20	0.101	0.113	0.119
	0.30	0.091	0.101	0.106
	0.40	0.086	0.094	0.098
	0.50	0.082	0.090	0.094
0.9	0.05	0.054	0.064	0.068
	0.10	0.044	0.051	0.055
	0.20	0.035	0.040	0.043
	0.30	0.031	0.035	0.037
	0.40	0.028	0.032	0.034
	0.50	0.027	0.031	0.032

Table 2

The value of coefficient φ when changing parameters α, P and β

α	P	Value of φ at β, which is equal to:		
		1	2	3
0.6	0.20	0.334	0.212	0.156
	0.30	0.343	0.219	0.161
	0.40	0.353	0.227	0.168
	0.50	0.364	0.236	0.175
0.7	0.15	0.366	0.231	0.169
	0.20	0.371	0.235	0.172
	0.30	0.381	0.243	0.179
	0.40	0.392	0.252	0.186
	0.50	0.403	0.262	0.194
0.8	0.10	0.388	0.244	0.178
	0.20	0.398	0.252	0.185
	0.30	0.409	0.261	0.192
	0.40	0.421	0.271	0.200
	0.50	0.434	0.281	0.208
0.9	0.05	0.399	0.250	0.182
	0.10	0.405	0.255	0.186
	0.20	0.416	0.263	0.193
	0.30	0.427	0.273	0.200
	0.40	0.440	0.283	0.203
	0.50	0.453	0.294	0.217

Table 3 gives the calculated values of n depending on parameters α, P and β at $\Delta = 10\%$.

Table 3

Calculated values of the number of layers n when changing α, P and β

α	P	Value of n at β, which is equal to:			
		1	2	3	4
0.6	0.20	3.03	1.93	1.54	1.35
	0.30	3.05	1.95	1.56	1.35
	0.40	3.10	1.98	1.58	1.36
	0.50	3.18	2.02	1.61	1.35
0.7	0.15	2.93	1.89	1.51	1.31
	0.20	2.93	1.89	1.51	1.31
	0.30	2.97	1.91	1.53	1.32
	0.40	3.04	1.94	1.55	1.34
	0.50	3.13	1.99	1.59	1.37
0.8	0.10	2.81	1.82	1.47	1.28
	0.20	2.83	1.83	1.47	1.28
	0.30	2.89	1.86	1.50	1.30
	0.40	2.97	1.91	1.53	1.32
	0.50	3.07	1.96	1.57	1.36
0.9	0.05	2.68	1.75	1.42	1.23
	0.10	2.68	1.75	1.42	1.23
	0.20	2.73	1.78	1.44	1.25
	0.30	2.81	1.82	1.47	1.28
	0.40	2.90	1.87	1.50	1.30
	0.50	3.01	1.93	1.54	1.34

Tables 4, 5 give the calculated content of elements according to the formula

$$Me^n = Me_H - \left(Me_H - Me_O\right) \cdot \left(\frac{\varphi}{1-\delta}\right)^n, \tag{14}$$

taking into account the expressions for calculating δ (9) and φ (10) during surfacing with some complex-alloyed powder tapes.

Table 4

Dependence of the composition of the metal surfaced with the PL-3X4V3F powder tape on the number of layers

α	P	β	Layer No.	Chemical composition of the surfaced layer, %						
				C	Mn	Si	Cr	V	W	Ti
0.6	0.2	2	1	0.17	0.42	0.42	2.78	0.42	2.43	0.14
			2	0.23	0.54	0.54	3.63	0.54	3.17	0.18
			3	0.24	0.58	0.58	3.89	0.58	3.40	0.19
		3	1	0.19	0.46	0.46	3.09	0.46	2.71	0.15
			2	0.24	0.57	0.57	3.79	0.57	3.32	0.19
			3	0.25	0.59	0.59	3.95	0.59	3.46	0.20
0.8	0.1	2	1	0.18	0.43	0.43	2.87	0.43	2.51	0.14
			2	0.23	0.55	0.55	3.68	0.55	3.22	0.18
			3	0.24	0.59	0.59	3.91	0.59	3.42	0.20
		3	1	0.20	0.48	0.48	3.17	0.48	2.77	0.16
			2	0.24	0.57	0.57	3.83	0.57	3.35	0.19
			3	0.25	0.59	0.59	3.96	0.59	3.47	0.20

Table 5

Dependence of the composition of the metal surfaced with the PL-5X3V3MFS powder tape on the number of layers

α	P	β	Layer No.	Chemical composition of the surfaced layer, %						
				C	Mn	Si	Cr	V	Mo	W
0.7	0.3	2	1	0.35	0.35	0.49	2.43	1.19	0.70	2.31
			2	0.46	0.46	0.64	2.64	1.55	0.91	3.01
			3	0.49	0.49	0.68	2.82	1.65	0.97	3.21
		3	1	0.39	0.39	0.55	2.26	1.32	0.78	2.57
			2	0.48	0.48	0.67	2.76	1.62	0.95	3.14
			3	0.49	0.49	0.69	2.87	1.68	0.99	3.26
0.9	0.1	2	1	0.37	0.37	0.51	2.12	1.24	0.73	2.41
			2	0.46	0.46	0.65	2.69	1.58	0.93	3.06
			3	0.49	0.49	0.69	2.84	1.67	0.98	3.24
		3	1	0.40	0.40	0.56	2.33	1.37	0.80	2.65
			2	0.48	0.48	0.67	2.79	1.63	0.96	3.17
			3	0.50	0.50	0.69	2.88	1.69	0.99	3.27

Our equations constitute a complete algorithm for calculating the chemical composition of the metal surfaced with a powder tape by the method of multilayer surfacing, taking into account the shares of the main and surfaced metal, the metal of the previous roller in the next and the relative surfacing step.

5. 2. Construction of a mathematical model for choosing the geometry of multilayer surfacing

When determining the conditions under which the waste of surfaced metal after the final grooving of the surfacing body will be minimal, it is necessary to take into account that the cross-sectional area of the reinforcement of the roller after grooving should be maximum.

The length of the *MC* segment (Fig. 1) is equal to the thickness of the surfaced layer after grooving

$$MC=\sqrt{h_1^2-\left(\omega\cdot h_1\right)^2}=h_1\sqrt{1-\omega^2}. \quad (15)$$

Then the area of the reinforcement of the roller after grooving will be equal to

$$F_M=2F_{OPMC}=Hh_1\sqrt{1-\omega^2}=$$
$$=h_1 b\alpha\sqrt{1-\omega^2}=b^2P\alpha\sqrt{1-\omega^2}. \quad (16)$$

If the grooving of the surfaced roller is not performed, then, as can be seen from Fig. 2 and formula (16), the area of the roller reinforcement will be maximum at $\omega=0$ and is equal to $b^2P\alpha$. From (10) it is seen that in this case

$$\alpha=1-2P, \quad (17)$$

and the area of reinforcement of the surfaced roller

$$F_M=b^2P(1-2P). \quad (18)$$

To study the maximum of function (18), it is necessary to find its derivative with respect to *P* and equate it to zero. Then, $(P-2P^2)'=1-4P=0$; $P=0.25$.

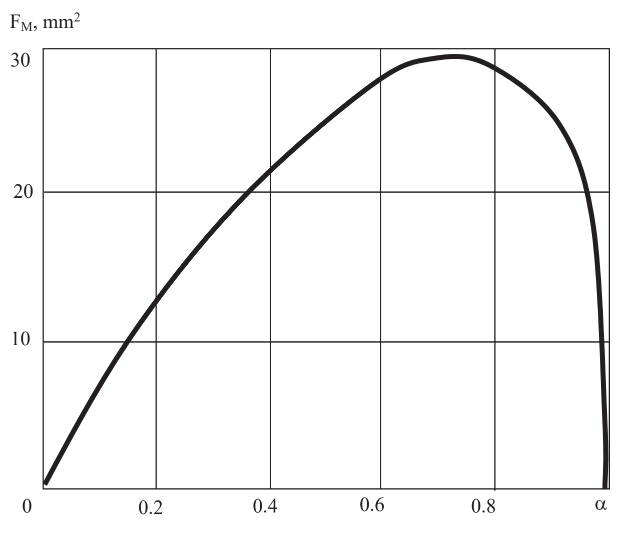

Fig. 2. Dependence of area F_M on the relative surfacing step α ($h_1=4$ mm, $b=15$ mm)

Thus, if the grooving of the surfaced roller is not performed, then the surfacing with a powder belt must be carried out under modes that provide the relation

$$P=\frac{h_1}{b}=0.25.$$

In this case, the relative step α will be equal to 0.5.

In fact, the value $P=0.25$ is usually achieved. But if the grooving of the surfaced roller is not performed, the surfacing is recommended to be carried out in this case with a relative step α, which is selected from formula (17).

To obtain the maximum cross-sectional area of the roller reinforcement after finish turning, if machining is performed, function (16) should be investigated for the maximum in variable α. For this purpose, it is necessary to find its derivative taking into account the fact that the parameter ω is also a function of α

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

As a result, the equation will take the form:

$$1-\omega^2-\alpha\omega\omega'=0.$$

If we change ω based on formula (10), we can obtain

$$1-\left(\frac{\alpha+2P-1}{2P}\right)^2-\alpha\frac{\alpha+2P-1}{2P}\cdot\frac{1}{2P}=0.$$

After the transformations, one can get a quadratic equation:

$$4P^2-\left(\alpha+2P-1\right)^2-\alpha\left(\alpha+2P-1\right)=0;$$

$$4P^2-\alpha^2-4P^2-1-4P\alpha+$$
$$+2\alpha+4P-\alpha^2-2\alpha P+\alpha=0;$$

$$-2\alpha^2-6\alpha P+3\alpha+4P-1=0;$$

$$2\alpha^2+\left(6P-3\right)\alpha+\left(1-4P\right)=0.$$

After solving the quadratic equation, the result will take the form

$$\alpha=\frac{-\left(6P-3\right)\pm\sqrt{(6P-3)^2-4\cdot 2\left(1-4P\right)}}{4}=$$
$$=\frac{3-6P\pm\sqrt{36P^2-4P+1}}{4}.$$

Analysis of this solution revealed that it is necessary to take a larger root. Then the optimal value of the relative step of surfacing will be equal to

$$\alpha=0.75-1.5P+0.25\sqrt{36P^2-4P+1}. \quad (19)$$

The next step is to find the area of waste cross-section of the surfaced roller reinforcement after finishing grooving (Fig. 1)

$$F_O = 2\left(h_1 - MC\right)\left(H/_2 - \omega h_1\right) +$$
$$+2\int_0^{\omega h_1}\left(\sqrt{h_1^2 - x^2} - MC\right)\mathrm{d}x =$$
$$= 2h_1\left(1-\sqrt{1-\omega^2}\right)\left(H/_2 - \omega h_1\right) +$$
$$+2\int_0^{\omega h_1}\left(\sqrt{h_1^2 - x^2} - h_1\sqrt{1-\omega^2}\right)\mathrm{d}x =$$
$$= \left(h_1 H - 2h_1^2\omega\right)\left(1-\sqrt{1-\omega^2}\right) +$$
$$+2\left(\frac{h_1^2}{2}\arcsin\frac{x}{h_1} + \frac{x}{2}\sqrt{h_1^2 - x^2} - h_1 x\sqrt{1-\omega^2}\right)\Bigg|_0^{\omega h_1} =$$
$$= \left(h_1 H - 2h_1^2\omega\right)\left(1-\sqrt{1-\omega^2}\right) + h_1^2\arcsin\omega +$$
$$+h_1^2\omega\sqrt{1-\omega^2} - 2h_1^2\omega\sqrt{1-\omega^2}.$$

Based on $H = b\alpha$, $h_1 = bP$, we obtain

$$F_O = \left(b^2\alpha P - 2b^2P^2\omega\right)\left(1-\sqrt{1-\omega^2}\right) +$$
$$+b^2P^2\left(\arcsin\omega - \omega\sqrt{1-\omega^2}\right) =$$
$$= b^2P\left[\begin{gathered}\left(\alpha - 2P\omega - \left(1-\sqrt{1-\omega^2}\right)\right) + \\ +P\left(\arcsin\omega - \omega\sqrt{1-\omega^2}\right)\end{gathered}\right]. \qquad (20)$$

From (20) it is seen that if $\omega = 0$, then $F_O = 0$, i.e., the grooving of the surfaced metal is not produced in this case, and there is no metal waste. The fraction of metal remaining after grooving $\gamma = F_M / (F_M + F_0)$ can be found

$$F_M + F_O = b^2P\alpha\sqrt{1-\omega^2} +$$
$$+b^2P\left[\begin{gathered}\alpha\left(1-\sqrt{1-\omega^2}\right) - 2P\omega + \\ +2P\omega\sqrt{1-\omega^2} + P\cdot\arcsin\omega - P\omega\sqrt{1-\omega^2}\end{gathered}\right] =$$
$$= b^2P\left(\alpha - 2P\omega + P\omega\sqrt{1-\omega^2} + P\cdot\arcsin\omega\right).$$

Hence

$$\gamma = \frac{\alpha\sqrt{1-\omega^2}}{\alpha + P\left(\arcsin\omega + \omega\sqrt{1-\omega^2} - 2\omega\right)}. \qquad (21)$$

Table 6 gives the optimal values of the surfacing step α with a powder tape, calculated according to expressions (16) and (18) if the surfacing metal is not grooved and if it is.

Table 6

Optimal values of the relative surfacing step α

P	Calculating α from formula:	
	(16)	(18)
0.05	0.90	0.911
0.10	0.80	0.845
0.15	0.70	0.800
0.20	0.60	0.770
0.25	0.50	0.750
0.30	0.40	0.736
0.35	0.30	0.726
0.40	0.20	0.718

Fig. 3 shows plots of dependence of the cross-sectional area of the reinforcement of the roller after machining F on the relative surfacing step α and the roller parameter P.

Fig. 4 shows plots of change in the fraction of metal remaining after machining γ from the relative surfacing step α and the roller parameter P.

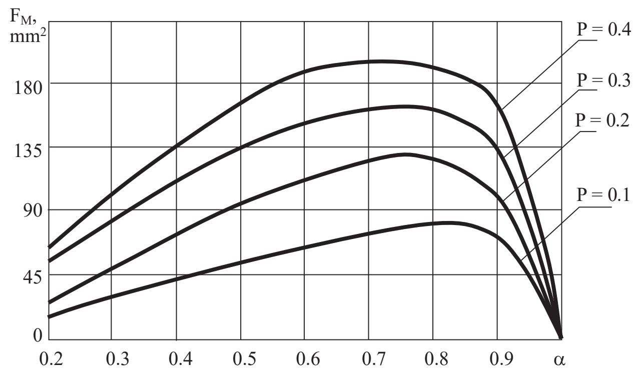

Fig. 3. Dependence of area F_M on the surfacing parameters α and P ($b = 30$ mm)

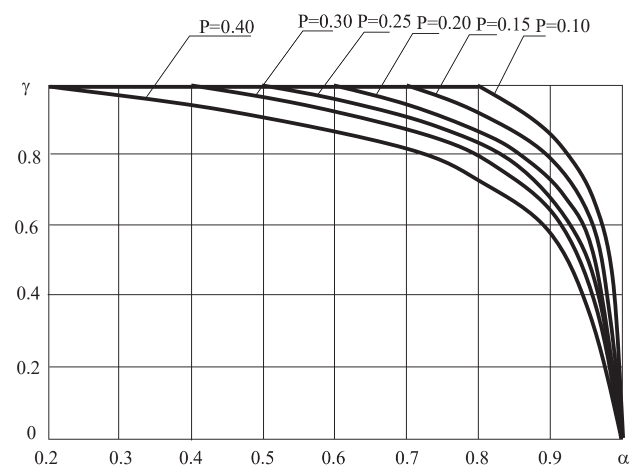

Fig. 4. Dependence of the proportion of metal γ remaining after grooving on α and P

Our equations constitute a complete algorithm for selecting the geometry of multilayer surfacing, taking into account the minimum waste of surfacing metal after the final grooving of the surfaced layer.

6. Theoretical and experimental study on the formation of a wear-resistant layer surfaced with a powder tape: results and summary

In order to save energy and alloying additives when compensating for wear, it is necessary to reduce the amount of penetration. Experimental and theoretical studies on the formation of the chemical composition of the surfaced metal in related papers [12–15] were performed for single-pass surfacing. The generalization of known models in the case of multi-pass restoration of worn parts has low reliability. This is due to the fact that the actual geometry of the formation of the rolls is not taken into account (Fig. 1) even when taking into account the coefficients of participation of the base and surfaced metal in the formed layer.

A feature of the proposed expressions (9) and (11) is the consideration of the features in the formation of geometric parameters and the chemical composition of the surfaced metal layer during wide-layer multi-pass surfacing. Analysis of our results from computational studies using the proposed mathematical model (Tables 1, 2) reveals that with an increase in the roll parameter *P*, the coefficient δ decreases and φ increases. An increase in the surfacing step α leads to a decrease in δ and an increase in φ. With an increase in the gain factor β, parameter δ increases, and parameter φ decreases.

As can be seen from Table 3, with an increase in the roller parameter *P*, the value of *n* increases. With an increase in the relative surfacing step α, *n* decreases. The gain factor β has the greatest influence on the number of layers *n*. When increasing from 1 to 4, the calculated value of *n* decreases from 2.7–3.2 to 1.2–1.4.

Thus, analysis of Table 3 reveals that the powder tape welding must be carried out under modes that provide low values of parameter *P*, i.e., the ratio of the height of the reinforcement of the roller h_1 to the width of the roller *b* ($P \leq 0.3$) and with a relative surfacing step α of at least 0.7. In this case, if the coefficient $\beta \geq 2$, then the required chemical composition of the surfaced metal will be achieved already in the second layer of surfacing.

When surfacing, the composition of the surfaced metal 3X4V3F (0.25% C; 0.6% Mn; 0.6% Si; 4.0% Cr; 0.6% V; 3.5% W; 0.2% Ti) (Table 4) is achieved already in the second layer of surfacing. When surfacing with powder tape PL-3X4V3F ($\alpha = 0.75$; $P = 0.15$; $\beta = 2.8$) in the second layer, the following was obtained: 0.24% C; 0.58% Mn; 0.62% Si; 4.1% Cr; 0.57% V; 3.54% W; 0.21% Ti.

The composition of the surfacing metal 5X3V3MFS (0.5% C; 0.5% Mn; 0.7% Si; 2.9% Cr; 1.7% V; 1.0% Mo; 3.3% W) with an error of slightly more than 10% is also achieved in the second surfacing layer (Table 5). When surfacing with powder tape PL-5X3V3MFS ($\alpha = 0.8$; $P = 0.25$; $\beta = 3.2$) in the second layer, the following was obtained: 0.52% C; 0.47% Mn; 0.65% Si; 3.1% Cr; 1.66% V; 0.96% Mo; 3.21% W.

Thus, equations with high informativeness have been proposed for calculating with sufficient accuracy the chemical composition of the surfaced layer, taking into account the shares of the main and surfaced metal, and the metal of the previous roller in the future. The modeling results are consistent with the experimental data obtained. The application of the proposed mathematical model makes it possible under industrial conditions to predict the expected result and select the optimal recovery modes for parts operating under conditions of intensive wear. Our results are also relevant in additive technologies, part of which is arc surfacing with powder electrodes of various designs, when it is necessary to fabricate an article by sequentially applying layers.

When solving the problem of building a mathematical model for forming the geometry of a multilayer surfacing, taking into account the minimum waste of surfaced metal after the final grooving of the surfaced layer, it was established that the maximum area F_M is achieved at α calculated from formula (18). This allows for the best formation of the surfaced layer, since each subsequent layer of multilayer surfacing is applied to the flat surface of the previous layer. It has been established that when α changes from 0 to the value of $1 - 2P$, the value of area F_M increases linearly according to formula $b^2 P\alpha$. With a further increase in the step α, the change in the F_M value occurs nonlinearly according to formula (15). It has also been established (Fig. 4) that when α increases to the value of $(1 - 2P)$, the value of $\gamma = 1$. Then parameter γ monotonically decreases to zero. From the comparison of the calculated and experimental data, it is clear that the calculation according to the given expressions gives good consistency of the results.

Since the choice of the surfacing geometry ensured the minimization of waste during subsequent machining, in addition to saving surfacing materials and reducing labor intensity, an increase in the quality of the surfaced layer is also ensured. This is due to the fact that each subsequent layer is applied to the flat surface of the previous one. In another case [14, 15], the layer is formed by fusing individual rollers, each surfacing occurs on the curved surface of the previous one, which changes the shape of the melted and surfaced particles.

Analytical description of regularities in forming the geometry of wide-layer surfacing with a powder tape makes it possible to solve technological problems under industrial conditions of improving the quality of the surfaced metal, increasing the productivity of the process, as well as resource and energy saving when depositing complex-alloyed wear-resistant alloys. It also makes it possible to determine the steps of controlling the process of forming the surface geometry in a wide range of surfacing productivity, as well as to model the restoration of cylindrical, conical, and flat surfaces taking into account the spatial orientation of the restored area.

When performing wide-layer multi-pass surfacing, the number of independent factors increases and, as a result, makes statistical methods for planning multifactor experiments ineffective. It is proposed to solve the optimization problems of the technological process of arc surfacing with powder tapes based on mathematical modeling of the formation of a seam of a given chemical composition with a minimum allowance for subsequent machining. The proposed mathematical models make it possible to correctly take into account the effect of the technological parameters of surfacing that affect the formation of a wear-resistant layer, namely the surfacing step, the weld reinforcement coefficient, the share of the metal of the previous roller in the next, the base metal in the roller metal and the metal remaining after machining.

From a practical point of view, the implementation of the proposed mathematical models will make it possible to increase the productivity of the process of surfacing complex-alloyed wear-resistant alloys. An applied aspect of the use of our scientific result is the possibility of increasing the quality indicators of the technological process.

Our methodological approach and calculation algorithm could be used in arc surfacing with electrode material of various designs (powder tapes, flux cored wires). However, it is necessary to take into account peculiarities in the formation of the geometry of the surfacing roller in each specific case and make appropriate adjustments to the proposed mathematical model.

The area of further research is the development of a software package to ensure fast and effective visualization of results from theoretical and experimental studies on the formation of the surfacing layer.

7. Conclusions

1. A mathematical model has been proposed for calculating the chemical composition of the metal surfaced by a powder tape, taking into account the shares of the main and surfaced metal, the metal of the previous roller in the next and the relative step of surfacing. It was established that multilayer surfacing by a powder tape must be carried out

under modes that provide low values of the ratio of the height of the reinforcement roller to its width (parameter $P \leq 0.3$) and with a relative surfacing step $\alpha \geq 0.7$. At the same time, if coefficient $\beta \geq 2$, then the required chemical composition of the metal will be achieved already in the second layer of surfacing.

2. A mathematical model has been proposed for the formation of the geometry of multilayer surfacing, taking into account the minimum waste of surfaced metal after the final grooving of the surfaced layer. It was shown that to obtain minimal metal waste after machining of the surfacing layer with a powder tape, it is necessary to conduct it with a relative step α, the optimal value of which is within 0.75–0.90, depending on the roller parameter P. It should be taken into account that the value of the metal fraction γ remaining after grooving is $\gamma = 1$ when α increases from 0 to the value $(1 - 2P)$, and then monotonically decreases to zero.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Valeriy Kassov: Conceptualization; Methodology; Supervision; Project administration. **Olena Berezshna**: Writing – review & editing, Visualization. **Svitlana Yermakova**: Formal analysis; Validation. **Svetlana Malyhina**: Writing – review & editing, Visualization. **Dmytro Turchanin**: Writing – original draft; Visualization.

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