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Determination of the optimal allowances for machining of parts with coatings

Kustov V. V.

PhD in Technical Sciences
Ivano-Frankivsk National Technical University of Oil and Gas

Ropyak L. Ya.

PhD in Technical Sciences
Ivano-Frankivsk National Technical University of Oil and Gas

Makoviychuk N. V.

Candidate of Physical and Mathematical Sciences
Ivano-Frankivsk Department of Pidstryhach Institute for Applied Problems of Mechanics and Mathematics National Academy of Sciences of Ukraine

Ostapovich V. V.

Ivano-Frankivsk National Technical University of Oil and Gas

Abstract
The processes of turning and grinding of coatings sprayed by the electric arc and electroplating methods were studied. Allowance was removed layer by layer and the roughness of the processed surface was measured. The mathematical processing of the research results was carried out using the methods of mathematical statistics and also mathematical models were built. The occurrence depth of the processed surfaces with lower roughness for

one-layer coating of steel, aluminum and chromium was established, as well as for two-layer composite coatings with a steel matrix. It was shown that for the latter the optimum value of the roughness achieved in the process of removing the smaller allowance for machining compared to one-layer.

Key words: ELECTRIC ARC SPRAYING, WIRE, POWDER PARTICLES, COMPOSITE COATING, ELECTROPLATED COATING, ALLOWANCE FOR MACHINING, SURFACE ROUGHNESS

Introduction

When making machine parts their working surfaces should be coated, and in many cases further machining is required to achieve the specified accuracy figures of size, shape and mutual arrangement of surfaces and their roughness, which is particularly relevant for rods and plungers of pumps. These characteristics are known to significantly affect the implementation by parts their service purpose in the composition of the machinery. Achieving the part surface quality parameters is carried out by cutting (turning, grinding) removing of material layers from its workpiece in the form of allowance. Defining of rational allowances for machining is an important technical and economic problem of mechanical engineering and a number of conditions are imposed on its solving. In particular, conservative values of allowances lead to the fact that the residual amounts of defect layer could be found on the processed surfaces, the obtaining of dimensional accuracy and surface roughness will not be guaranteed. This leads to an increase of rejection and, as a consequence, raises costs of parts manufacturing process. On the other hand, overestimated values of allowances lead to excessive costs of materials for production, increased labor-output ratio, rising of energy resources expenditure, cutting tools, and this in turn results in increase of cost supplement of machine parts production.

Analysis of recent researches and publications

Mechanical processing of coating is paid considerable attention in many investigators [1 - 3], including also the analysis of the processing accuracy [4]. In [5] was proposed to define allowance for machining of parts with sprayed coatings depending on their thickness from the strength conditions. This allowance defining method leads to the removal of the coating layer of significant thickness.

The authors of [6] have developed a method for determining the allowance for machining of parts with gas-thermal coatings comprising processing the sample with a layer by layer coating removal and taking into account the availability of the defect layer which is based on microhardness determination. At first cross straight grinding of the coated sample is made, than the microhardness of the coating in depth with a pitch is determined corresponding to the depth of cut when layered mechanical processing. Then layer by layer mechanical processing of coated sample is carried out with the same pitch and after each passage the microhardness of the treated surfaces is determined. Then these values of microhardness are compared and according to the microhardness criterion the value of layer, which is subjected to hammering harden during mechanical processing is taken into account. And the allowance is determined. It is equal to the total value of the defective layers thicknesses before the start of qualitative area except of the layer subjected to hammering harden.

According to studies results [7], which are aimed at establishing patterns of change in surface roughness when layered mechanical processing of coatings the allowance is proposed to determine on the total thickness of the removed layer, which provides a minimum roughness of the processed surface.

In [8] the definition of allowances for machining of electroplated coatings was studied, but attention was not pay to the dependence of surface roughness value on the value of the machining allowance.

In researches [9] the surface roughness of the metal coatings processed by grinding was studied, and in [10, 11] the dependence of surface roughness on the cutting conditions for grinding of ceramic coatings was determined.

Analysis of [1 - 11] has shown, that they relate to mechanical processing of one-layer wear-resistant coatings, i. e. a solid top layer is removed by cutting and transform it into turnings, resulting in significant costs on the parts hardening. At the same time in the technical and patent literature there is almost no information about defining allowances for machining of two-layer coatings.

Work objective is to define patterns of change in the roughness of the treated surfaces in depth of one- and two- layer composite coatings and to establish the value of the optimum cutting depth (allowance), in which a minimum surface roughness is provided.

The presentation of the main results of the study

Studies were conducted on steel (steel 45) samples of cylindrical shape, the surface of which was coated with layer of different thickness. Coatings of steel 45 were sprayed $h = 0.6; 1.2; 1.8; 2.4$ mm thick, and also from aluminum and its alloy D16 h = 1.2; 1.8 mm thick. For coatings spraying the plant developed by us [12] was applied allowing forming the coating by the electric arc method from wires as well as from using wires and powder materials, which were introduced into metal-flow of electric arc plant from the feeder. Investigations were carried out on one-layer coatings sprayed from the wire material (steel, aluminum, alloy D16) and two-layer composite coatings consisting of lower working composite layer (a particles mixture of the base material from steel wires and powder particles of tungsten carbide), and technological upper layer sprayed only from wires. Some experiments were also carried out on electroplated chromium coatings h = 0.08; 0.3 mm thick.

Axial section of cylindrical parts with a one-layer and combined two-layer composite coatings are shown in Fig. 1

After completion of the spraying process of samples the layered mechanical processing on screw-cutting lathe with a predetermined pitch was carried out. Grinding of electroplated chromium coatings were performed on cylindrical grinding machine.

Types of turnings produced during the turning process of samples from solid and sprayed steel are shown in Fig. 2.

The photographs shows that in the process of turning handling of the sample turnings are formed from steel in the form of rings and small groundling (Fig. 2a), and in the process of turning of the sprayed steel coatings - in the form of small grit, pieces and die cutting (Fig. 2b). It is due to the specific structure of sprayed coating: lamellae like, layerage and porosity.

The roughness value of the samples treated surfaces were measured on profilograph - profilometer by scanning along the generatrix of cylindrical samples.

To achieve work objective the mathematical models were built. They analytically describe the dependence of surface roughness on the depth of the cut coating layer and allow us to determine the most probable optimal parameters, as well as to establish the dependence of optimal values its roughness in depth for sprayed and electroplated coatings of varying thickness during their layered mechanical treatment.

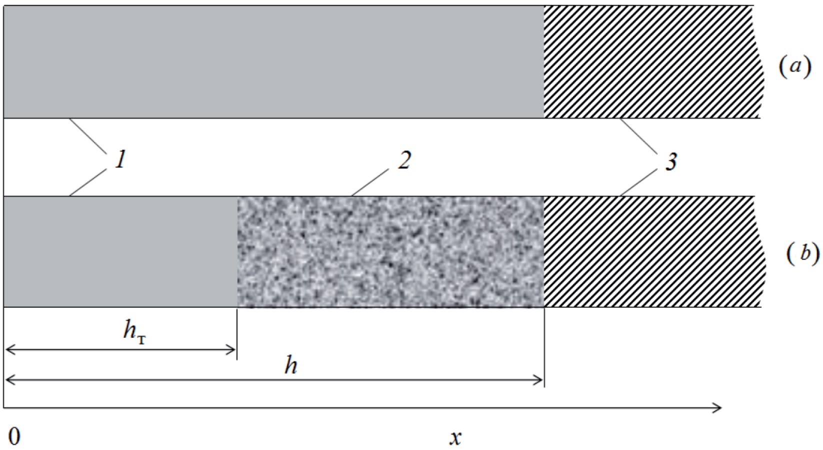
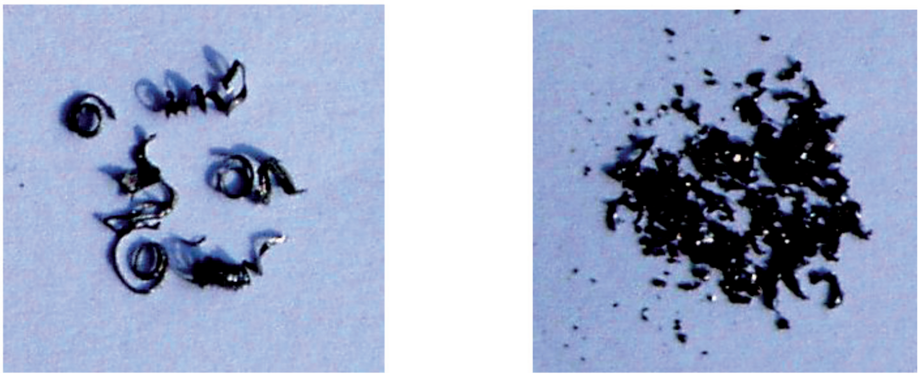


Figure 1. Scheme of a one-layer sprayed or electroplated coating(a) and two-layer composite sprayed coating(b) 1 - layer of sprayed or electroplating coating, 2 - layer of sprayed composite coating 3 - steel base



a) b)

Figure 2. General view of the turnings when turning of cylindrical samples from solid steel (a) and sprayed with a steel coating (b)

When the graphical analysis of the correlation diagram of the roughness value experimental data depending on the thickness of removed by mechanical processing coating layer is established that the desired dependence will have a clearly pronounced nonlinear nature (Fig. 3 - 5). To identify the nature of connection between these factors and to build equations analytically described the basic tendency of this dependence the regression analysis methods were used.

In the regression analysis is usually necessary to perform three consecutive stages of research:

1) To determine the type of function f (selection of the model structure) to describe the desired dependence

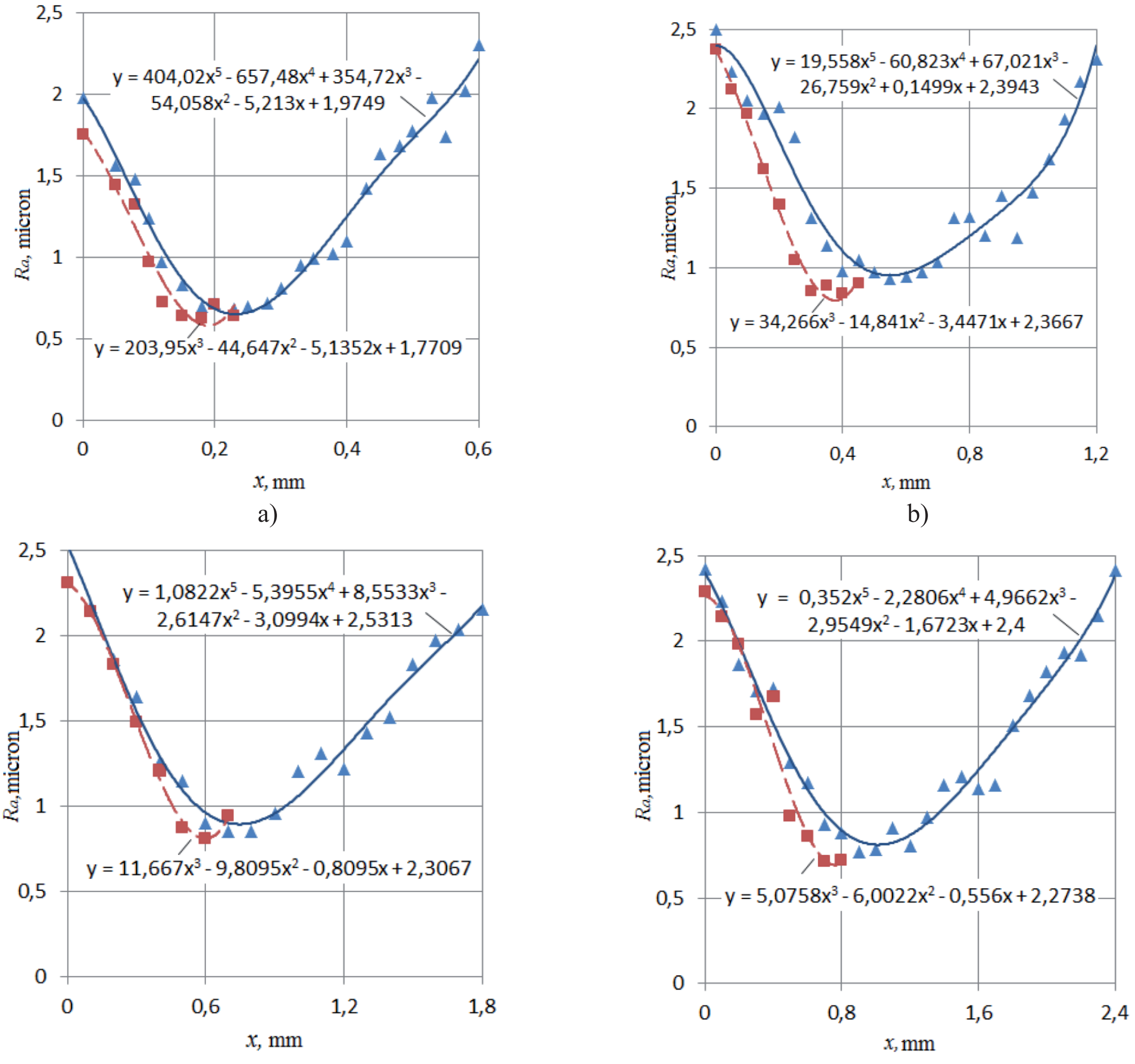
$$y_i = f(X_i, \alpha) + \varepsilon_i, \qquad (1)$$

where y_i – the dependent variable, $X_i = (x_{1,i}, ..., x_{k,i})$ – the value of the independent variables, for i-th observation, $\alpha = (\alpha_0, ..., \alpha_m)$ – vector of unknown parameters of the model to be evaluated, $\varepsilon_i = y_i - \tilde{y}_i$ – deviation between the experimental and theoretical data;

2) to carry out calculation of the unknown coefficients of the regression equation $\alpha_0, ..., \alpha_m$;

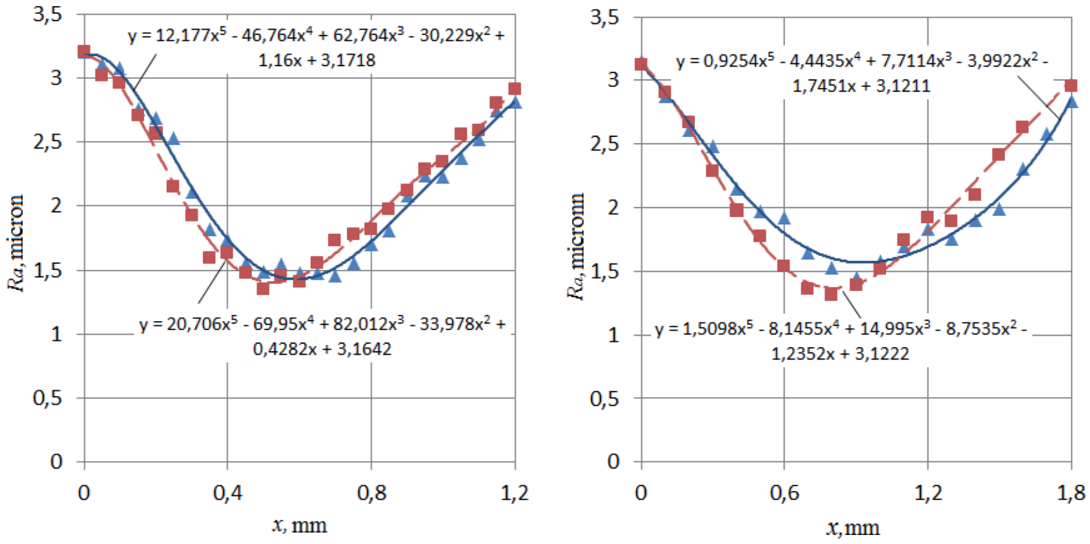
3) to assess the adequacy of the obtained mathematical model.

All three of these procedures can be performed comprehensively. Modern software packages can simultaneously build several types of equations to obtain estimates of their parameters, and then using corresponding criteria to choose the best model. As such criteria may be used: the maximum value of the determination coefficient, the maximum value of F-Fisher criterion, the minimum value of the residual variance, the minimum value of the equation standard error, normality of distribution of the residual a number of errors ε_i and others.



a) b) c) d)

Figure 3. The surface roughness dependence of the cut off layer depth for spraying steel coatings of various thicknesses (triangular markers – a one-layer coating; the square - a two-layer composite coating): a – h = 0.6 mm; b – h = 1.2 mm; c – h = 1.8 mm; d – h = 2.4 mm



a) b)

Figure 4. The surface roughness dependence of the cut off layer depth for one-layer sprayed coatings from aluminum alloys of different thickness (triangular markers - aluminum; square markers - alloy D16): a – *h* = 1.2 mm; b – *h* = 1.8 mm

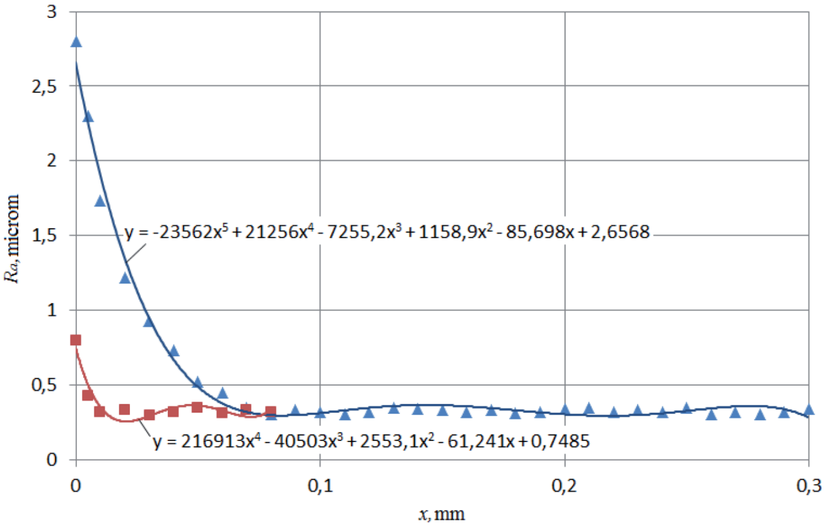


Figure 5. The surface roughness dependence of the cut off layer depth for one-layer electroplated chromium coatings of different thicknesses: square markers – *h* = 0.08 mm; triangular markers – *h* = 0.3 mm

The measurement results are shown in graphs (Figs. 3 - 5). Marked points represent the experimental values of roughness parameter R_a on accordance with value x of removed allowance by cutting when layered mechanical processing of samples for each of the above coating thicknesses.

Determining the type of regression function (1) that best approximates the correlation field was performed by trial and error method. Considering the nature of the studied parameters, the type of correlation fields and properties of mathematical functions for constructing the approximating lines power-polynomials were selected.

In the case of one independent parameter x – the thickness of the removed layer by cutting (allowance), and denote the processed surface roughness $R_a = y$, we obtain

$$y = \alpha_0 + \alpha_1 x + \alpha_2 x^2 + ... + \alpha_m x^m . \qquad (2)$$

Power m of polynomial (2) was selected from the condition of the maximum value of the determination coefficient (the variance ratio of conditional mathematical expectation in the total variance)

$$R^2 = \frac{\sum_{i=1}^{n}(\tilde{y}_i - \bar{y})^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} = 1 - \frac{\sum_{i=1}^{n}(y_i - \tilde{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \qquad (3)$$

and minimum value of residual variance

$$\sigma_{res}^2 = \frac{\sum_{i=1}^{n}(y_i - \tilde{y}_i)^2}{n-m-1}. \qquad (4)$$

Here y_i, $\tilde{y}_i$ – experimental and theoretical values of roughness respectively, $\overline{y}$ – the mathematical expectation of the dependent variable. The determination coefficient of the regression (3) varies within $0 \le R^2 \le 1$ and approaches to one if the test values are related by functional connection ($y_i = \tilde{y}_i$) or – to zero if the input and output variables are independent.

Raising of power *m* of approximating polynomial usually leads to a more accurate approximation the trend line to the experimental data, but at the same time when applying high orders models the influence of random errors experiment results are increased. Also, when performing the exponentiation for the formula of high orders, rounding errors have become so large that they can nullify the benefit from high order regression.

Fig. 5 shows that when decreasing the thickness of the electroplated chromium coating the allowance value for grinding is reduced. For coatings with the thickness of $h = 0.08$; 0.3 mm the allowance for grinding is 12; 27 % from their total thickness respectively. With further increase in the depth of a cut off layer machined surface roughness of coatings remains unchanged.

In our case the most acceptable results were obtained when approximating the measurement results of the processed surface roughness parameter of sprayed steel coatings by polynomials of third (two-layer composite coating) and fifth order (one-layer coating) in accordance with smaller and larger amounts of experimental measurement points $n = 8...10$ and $n = 25$. The graphs of obtained dependences are shown in Fig. 3.

For one-layer coatings sprayed from aluminum and its alloy D16, acceptable results were obtained by approximating the results of measurements of the processed surface roughness parameter by fifth power polynomials (Fig. 4).

For application of one layer electroplated chromium coatings acceptable results were obtained in approximating the measurements results of the processed surface roughness parameter by polynomials of fourth (thin coating $h = 0{,}08$ mm) and fifth powers (thick coating $h = 0{,}3$ mm) respectively (Fig. 5).

The maximum value on the abscissa axis corresponds to the thickness of the applicated coating *h* in each of the cases considered. As can be seen from the figures, the main tendency of change in the surface roughness parameter depending on the depth of the cut off layer is practically the same for studied thicknesses of both types of sprayed coatings, and the appearance of these curves differ practically within the statistical error. Moreover, the curves with square markers corresponding to two-layer sprayed composite coatings lie somewhat below the curves marked by triangles (sprayed coating). That is, for all shears of equal thickness, the processed surfaces of the sprayed composite coating will have a smaller surface roughness as compared with one-layer.

Statistical estimates of parameters $\alpha_0,...,\alpha_m$ of the approximating dependences were obtained by the method of least-squares. The evaluation of the obtained coefficients significance was performed on the basis of *t* – criterion based on the 95% confidence coefficient and the number of freedom degrees $p - k - 1$, where *p* – the number of observations, *k* – the number of parameters in the regression equation. The adequacy of the approximating dependence in general on Fisher criterion was checked. Estimated values of the criteria and statistical estimates of regression equations were performed in STATISTICA software environment. The main results of researches for the coatings are shown in Tables 1 and 2 respectively.

Comparing the graphs of roughness variation for sprayed coatings of aluminum-based materials its smaller value for the D16 alloy should be noted, which may be due to its higher hardness when compared to aluminum. For the same reason the smaller depth of the processed surface with minimum roughness can be explained for the coatings with D16 as the same obtained at a solid material.

Further analysis of the obtained graphical dependence (Fig. 4) of changing the roughness for sprayed coatings of aluminum and aluminum alloy D16 on the steel base shows that their character is not significantly different from the graphic dependences obtained for the steel coating (Fig. 3). However, the occurrence depth of the processed surface with minimum roughness for the coating from both the aluminum and alloy D16 is slightly larger in comparison with steel, which is determined by the higher damping properties of aluminum. Due to this, the roughness of processed surfaces is larger. The damping ability will decrease as it approaches to the steel base, i. e. with a decrease in the thickness of the untreated surface residual layer.

On the basis of the built approximating dependences we can determine the location of the processed surface with minimal roughness with respect to the outer surface of the untreated sprayed coating, as well as to define the value of allowance x^* (total thickness of the cut off layers), that is necessary to obtain a minimum roughness of the working surface.

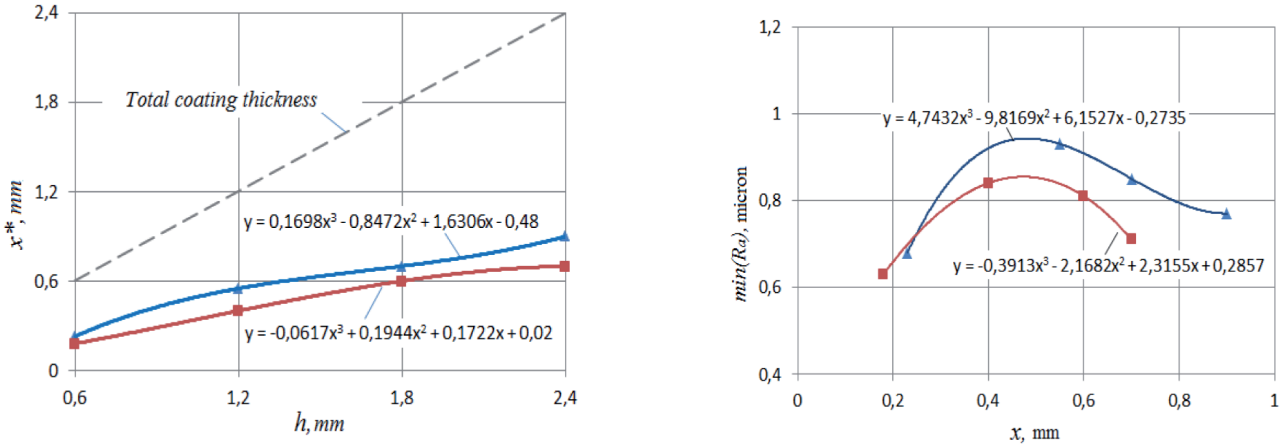
Table 1. Statistical estimates of the surface roughness parameter dependency on the processing depth of two-layer sprayed composite coatings with a steel matrix

h, mm	The regression equations for roughness calculation	R^2	σ^2_{res}	The equation significance at the level of reliability of 95%
0.6	$y = 203.95x^3 – 44.647x^2 – 5.1352x + 1.7709$	0.972	0.063	The statistically significant
1.2	$y = 34.266x^3 – 14.841x^2 – 3.4471x + 2.3667$	0.991	0.025	The statistically significant
1.8	$y = 11.667x^3 – 9.8095x^2 – 0.8095x + 2.3067$	0.998	0.004	The statistically significant
2.4	$y = 5.0758x^3 – 6{,}0022x^2 – 0.556x + 2.2738$	0.957	0.112	The statistically significant

Table 2. The statistical estimates of the surface roughness parameter dependencies on the processing depth of the one-layer sprayed and electroplated coatings

h, mm	The regression equations for roughness calculation	R^2	σ^2_{res}	The equation significance at the level of reliability of 95%
Sprayed coating of steel				
0.6	$y = 404.02x^5 – 657.48x^4 + 354.72x^3 – 54.058x^2 – 5.213x + 1.9749$	0.955	0.162	The statistically significant
1.2	$y = 19.558x^5 – 60.823x^4 + 67.021x^3 – 26.759x^2 + 0.1499x + 2.3943$	0.943	0.342	The statistically significant
1.8	$y = 1.0822x^5 – 5.3955x^4 + 8.5533x^3 – 2{,}6147x^2 – 3{,}0994x + 2{,}5313$	0.979	0.094	The statistically significant
2,4	$y = 0.352x^5 – 2.2806x^4 + 4.9662x^3 – 2.9549x^2 – 1.6723x + 2{,}4$	0.972	0.184	The statistically significant
Sprayed coating of aluminum				
1.2	$y = 12.177x^5 – 46.764x^4 + 62.764x^3 – 30.229x^2 + 1.16x + 3.1718$	0.987	0.106	The statistically significant
1.8	$y = 0.9254x^5 – 4.4435x^4 + 7.7114x^3 – 3.9922x^2 – 1.7451x + 3.1211$	0.982	0.083	The statistically significant
Sprayed coating of aluminum alloy D16				
1.2	$y = 20.706x^5 – 69.95x^4 + 82.012x^3 – 33.978x^2 + 0.4282x + 3.1642$	0.989	0.086	The statistically significant
1.8	$y= 1.5098x^5 – 8.1455x^4 + 14.995x^3 – 8.7535x^2 – 1.2352x + 3.1222$	0.988	0.075	The statistically significant
Electroplated chromium coating				
0.08	$y = –23562x^5 + 21256x^4 – 7255.2x^3 + 1158.9x^2 – 85.698x + 2.6568$	0.995	0.003	The statistically significant
0.30	$y = 0.352x^5 – 2.2806x^4 + 4.9662x^3 – 2.9549x^2 – 1.6723x + 2.4$	0.986	0.180	The statistically significant

Dependences of optimum allowance values for coatings of both types of different thickness, as well as the minimum roughness values for machining allowances with corresponding thickness of the coating is shown in Fig. 6. In this case, when four approximation centers (four thicknesses of coatings *h*: 0.6; 1.2; 1.8; 2.4 mm) cubic polynomials are interpolated curves ($\varepsilon_i = 0$, $R^2 = 1$). As can be seen from the figure the minimum roughness value of the processed surfaces for two-layer sprayed composite coatings in comparison with the one-layer sprayed coatings is achieved by removing the smaller machining allowance, and the dependence $\min(R_a)$ from *x* and the dependence of the coating of varying thickness is a monotonic.



a) b)

Figure 6. The dependence of the optimum allowance *x** for steel coatings of varying thickness (a) and determining of the minimum roughness allowances for machining of coatings of corresponding thicknesses (b) triangular markers - one-layer sprayed coatings; square - two-layer sprayed composite coatings

Achieving the minimum surface roughness when removing smaller machining allowances of sprayed two-layer composite coatings may be explained by a greater hardness of the composite working layer in comparison with hardness of the upper technological layer obtained only by spraying from steel wires.

The processed surface with minimum roughness and the coating layer on which it is formed can be used as a working if the part is a component unit of the friction couple and the special requirements are not imposed for its hardness. Otherwise, this surface is used as a basis for further vibroelektrospark alloying of steel coating or plasma electrolytic oxidation of the layer upper part of the aluminum coating to create a wear-resistant working layers.

Conclusion

On the basis of carried out studies results was found that:

1) the occurrence depth of the treated surfaces with lowest roughness for sprayed and electroplated coating depends on the total thickness of the coating and increases with its growth;

2) the optimum roughness value of the treated surfaces for sprayed composite coatings with a steel matrix in comparison with the steel sprayed one-layer coating is achieved by removing the smaller allowance for machining;

3) for electroplated chromium coatings the optimum occurrence depth of treated surfaces with minimal roughness was established and showed that its value was not changed during further cutting of coating.

In further researches we are going to investigate the influence of the number of coatings layers, matrix materials and powder particles used for forming composite coatings when electric arc spraying on the roughness of machined surfaces.

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