Process optimization of applying heat and wear proof coating to machine elements in complex acoustic field

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Abstract. The process of obtaining expected physical and mechanical properties of protective coating, which is applied on machine elements in complex acoustic field by electroacoustic method, is conducted with the use of highly concentrated sources of electric energy. Prediction of physical and mechanical properties of the reinforced surface of machine parts is made on the basis of the experimental design technique with nonorthogonal planning matrices. Mathematical models were tested for adequacy on the basis of Fisher’s variance ratio. A structural scheme for microprocessor control system of electroacoustic spray coating was developed. The physical basis of the mass transfer of materials to the substrate in a complex acoustic field is developed, which is done by transforming longitudinal vibrations into longitudinal-torsional ones, while the amplitude of the acoustic system oscillates from 5 to 15 micrometers. The use of longitudinal-torsional ultrasonic waveguides in this process and ultrafast cooling temperatures allow the formation of such elements as carbides, carbonitrides, intermetallics on the surface of the conductive material. The subsequent shock produced by the waveguide-electrode with a shift to the surface leads to irreversible microflow of the surface layer, which provide the specified parameters of the surface quality and its physical and mechanical properties (microhardness and roughness). The thickness of the sprayed layer is 6-8 micrometers, and the thickness of the plastically deformed layer is 30-45 micrometers.

1. Introduction
The problem of obtaining the predicted physical and mechanical properties and a given operating life of multifunctional composite heat and wear resistant protective coatings in the form of barrier layers and an increase in the operating life of engineering products and forming tools are directly linked. Among the variety of the latest highly efficient technological processes, the method of electroacoustic spray coating (ELASC) should be stood out. This method is innovative in the field of multifunctional composite coatings and allows forming nanocrystalline protective films on any conductive materials and substrates [1]. This technology is based on the use of the complex energy of an electric spark and a powerful longitudinal-torsional ultrasonic field.

The goal of the work is to optimize the process of obtaining heat and wear resistant protective coatings based on mass transfer of the electrode material and the subsequent formation of structures with predicted physical and mechanical properties by electroacoustic spraying.

2. Materials and Methods
In order to achieve the set goal, a generalized model of the process of applying protective coatings by the method of electroacoustic spraying was developed, a wide range of studies was carried out, which
required the use of specially developed for this purpose hardware and software package of the control system technologist.

The installation of electroacoustic spraying of multifunctional composite heat and wear proof coatings for machine parts is shown schematically in Figure 1.

The structural scheme of the electroacoustic spraying installation consists of: 1 - waveguide with an electrode at its end; 2 - the element being hardened; 3 - feedback sensor; 4 - acoustic system; 5 - ultrasonic generator; 6 - control system; 7 - electronic switch; 8 - power supply unit; C - energy storage unit.

Figure 1. Structural scheme of electroacoustic spray coating.

A model of the process of applying heat and wear resistant protective coatings during hardening of engineering products and forming tools is shown in Figure 2.

Figure 2. Model of applying of heat and wear resistant coating: G₁, G₁₂, G₂, G₃, G₄ - material shear modules; \( \vec{A}_n \) - vector describing the longitudinal component of ultrasonic vibrations of the acoustic system; \( \vec{A}_k \) - vector describing the torsional component of ultrasonic vibrations of the acoustic system; \( \vec{A}_p \) - resulting vector of complex acoustic field.

The source of acoustic energy in the system of applying heat and resistant protective coatings is an ultrasonic generator (UZG-1-1), to which an acoustic transducer (PMS 1-1) is connected. An acoustic waveguide is connected to the transducer through an acoustic transformer, forming a complex acoustic field with a frequency of 22 kHz. The microprocessor control system for supplying discharge pulses polls the inductive acoustic feedback sensor and generates a control action on the power energy storage, as a result of which, when the electrode is applied to the substrate surface, the system
commutes the discharge pulse of a given shape. As a result of a complex supply of a potential that changes in time and complex ultrasonic vibrations into the interelectrode gap, three phases of the electrode material arise: liquid, solid, and gaseous. The shape of the discharge pulse and its fronts are optimized according to the criterion of the maximum yield of the liquid phase of the electrode material, which provides the maximum value of mass transfer.

The material, which is obtained in the result of the complex action of highly concentrated energy sources and being in the liquid phase, is forced to form a channel that carries out mass transfer towards the negative pole of the hardened substrate, when combined with the kinetic energy and the electric field.

The electrode mounted on the opposite end of the acoustic speed concentrator, due to the peculiarities of its design, performs longitudinal-torsional vibrations, which have a powerful dispersing effect on the material in the liquid phase. In this case, the active volume of interaction with the environment of the liquid-phase material rapidly increases V₀ and N, C, O₂ and other elements from the environment enter the reaction.

Over the next period of time, the electrode substance is transferred to the substrate of the material, and ultrafast cooling temperatures as well as the combined action of highly concentrated energy sources of an electric spark and a complex acoustic field lead to the formation of an amorphous layer on the surface of the hardened product, which contains carbides, carbonitrides, and intermetallics, that add unique physical and mechanical properties to the coated layer.

Then, an ultrasonic waveguide-concentrator with an electrode attached to its end makes mechanical contact with shear, therefore leading to irreversible microplastic deformation of both the sprayed layer and the substrate.

At the next stage, the waveguide-concentrator is removed from the coated surface. The analysis of the synthesized structures as a result of using the electro-acoustic spray coating method shows that, based on the physical, mechanical and operational properties of the layers, they can be aggregated into composite layers that impede the break of crystal-lattice defects to the surface. The first composite layer will be formed by barriers with shear modulus G₁₂ and G₄, and the second one with G₂ and G₃ [2].

The presented generalized model for the synthesis of composite heat and wear resistant protective coatings by the method of electroacoustic spraying allows clarifying the effects of the formation of barriers that impede both the break of crystal-lattice defects (dislocations) to the surface and the increase in the operating life of agricultural engineering products by suppressing slip and increasing the microhardness of the surface layer of the processed product.

The process of coating by the method of electroacoustic spraying allows synthesizing a multifunctional composite heat and wear proof coating, the principle of which is based on the building up of hard alloys [3]. The first protective layer of the multifunctional composite coating is formed due to irreversible microplastic deformation of the surface layer of the substrate, and the second one is formed by an amorphous layer of the deposited electrode material with elements of carbides, carbonitrides, and intermetallics synthesized in the result of highly concentrated exposure to electric energy and a complex ultrasonic field.

The experimental design technique for nonorthogonal matrices was used in order to predict the main quality parameters of the processed agricultural engineering products and to optimize the process of applying multifunctional composite heat and wear resistant protective coatings according to the criterion of minimizing the costs.

A linear dependence model is taken as an example (1)

\[ \hat{Y} = B_0 + B_1 X_1 + B_2 X_2 + \ldots + B_{11} X_{11} + B_{12} X_{12} + \ldots + B_{22} X_2 X_2 \ldots \]  \hspace{1cm} (1)

A specialized application package was developed to process the obtained experimental data. The software approximates linear and non-linear models.
A matrix of levels of factors X and a matrix of experimental results with m, n, k are specified, where m is the number of rows for the matrix of input and output parameters; n is the number of columns of the matrix of input parameters; k is the number of columns of the matrix of output parameters. The coefficients of the regression equation are estimated using the least squares technique.

The calculation of the main parameters is carried out on a computer using the presented software package. In our case, when checking the “roughness” model for adequacy, we got a negative result, which indicates its invalidity. Therefore, it is necessary to adopt a new model, which is represented by expression (2)

\[ Y = B_{0} + B_{1}X_{1} + B_{2}X_{2} + B_{3}X_{3} + B_{4}X_{4} + B_{5}X_{5}X_{3} + B_{6}X_{6}X_{4} + B_{7}X_{7}X_{4} + B_{8}X_{8}X_{4} + B_{9}X_{9}X_{4} + B_{10}X_{10}X_{4} + B_{11}X_{11}X_{4} + B_{12}X_{12}X_{4} + B_{13}X_{13}X_{4} + B_{14}X_{14}X_{4}. \]

Let’s check the adequacy of the above model. According to the Fisher's ratio, determine the tabular value \( F_{\text{theor.}} = 2.8 \) for the level (0.95), and the experimental value \( F_{\exp.} = 0.431 \) respectively. The model is valid since \( F_{\text{theor.}} > F_{\exp.} \).

The model [4] was adopted based on the results obtained during a series of experiments devoted to the study of the roughness behavior of the surface layer of hardened samples during electroacoustic spray coating, and preliminary conclusions can also be drawn:
- the complex effect exerted during hardening of samples by electroacoustic coating causes a change in the roughness of the hardened surface layer depending on the processing conditions;
- the functional dependence of the roughness on the voltage applied to the electrode, the amplitude of the vibrations of the acoustic system, the clamping pressure and the supply values \( R_{s}(U_{P}, A, P, S) \);
- the strongest effect on the roughness of the obtained surface layer of hardened samples is exerted by the amplitude of the acoustic system vibrations and the supply values;
- a lesser effect on the roughness of the obtained surface layer of hardened samples is exerted by the voltage applied to the electrode and the clamping pressure;
- the final hardened layer has the same roughness in both longitudinal and lateral directions;

Using the method of optimal experimental design, it is required to define the dependencies of the main operational characteristics of machine elements: microhardness \( HV \) (4) and roughness \( R_{s} \) (5) on the operating modes of the station for electroacoustic application of multifunctional protective coatings. As a result, the following dependencies were obtained:

\[ HV = 5699.7 + 3339.6X_{1} + 711.8X_{2} + 170.2X_{3} + 341.2X_{4} + 384.1X_{5}X_{3} + 135.9X_{6}X_{4} + 624.4X_{5}X_{4} + 299.4X_{6}X_{4} - 210.9X_{1}X_{4} + 252.5X_{4}X_{4} - 683.7X_{3}X_{4} + 673.9X_{2}X_{4} - 514.2X_{1}X_{4}X_{4}. \]

\[ R_{s} = 0.77 + 0.058X_{1} - 0.088X_{2} - 0.034X_{3} + 0.105X_{4} + 0.024X_{5}X_{4} + 0.003X_{6}X_{4} - 0.028X_{1}X_{4} + 0.004X_{2}X_{4} + 0.050X_{3}X_{4} + 0.042X_{5}X_{4} + 0.089X_{6}X_{4} - 0.054X_{1}X_{4} - 0.022X_{2}X_{4} - 0.024X_{3}X_{4}. \]

where, \( X_{1} \) – voltage applied to the electrode; \( X_{2} \) – vibration amplitude of the acoustic system; \( X_{3} \) – clamping pressure; \( X_{4} \) – supply.

The above dependencies are rather complicated, therefore, the use of the obtained data in the analytical form for optimization is very difficult. In addition, the acceptable variation of the main modes, the so-called working range, imposes additional restrictions on obtaining the specified surface quality parameters.

3. Results

The goal is to minimize the values of the voltage \( U_{P} \) applied to the electrode and the amplitudes of the ultrasonic vibrations \( A \) for acceptable supply values \( S \) and a fixed value of the clamping pressure \( P \),...
provided that the required surface quality parameters are set - microhardness and roughness. For the required microhardness value, in accordance with expression (4), the dependency of the supply value on the voltage values on the electrode $U_P$ and the amplitude of ultrasonic vibrations $A$ is plotted [5].

A numerical solution of this expression with respect to the parameter $X_4$ and further three-dimensional interpolation were performed MATLAB program. The surface shape varies depending on the given microhardness value; the surface type for the value $HV = 7000$ is shown in Figure 3.

Figure 3. Surface $X_4=f(X_1, X_2)$ for $HV=7000$ when $X_3=0.5$; $X_1$ – voltage applied to the electrode; $X_2$ – vibration amplitude of the acoustic system; $X_3$ – clamping pressure; $X_4$ – supply.

Figure 4. Surface $X_4=f(X_1, X_2)$ for $Ra=0.63$ when $X_3=0.5$; $X_1$ – voltage applied to the electrode; $X_2$ – vibration amplitude of the acoustic system; $X_3$ – clamping pressure; $X_4$ – supply.

Figure 5. Intersection of surface graphs of quality parameters $HV = 7000$ and $Ra = 0.63$.

Similarly, surfaces can be obtained for the required value of the roughness parameter, in particular, for $Ra = 0.63$ (Figure 4).

A graphical interpretation of the corresponding level surfaces is shown in Figure 5.

The given figures represent a set of solutions of equations (4) and (5) with respect to the supply value $X_4$ for a fixed value of the clamping pressure $X_3$ in the range of acceptable voltage range on the electrode $X_1$ and the amplitude of ultrasonic vibrations $X_2$. The simultaneous solution of the two equations is the intersection of the surface graphs corresponding to each of the equations (Figure 5).

The projection of the set of solutions of the system of equations to the $x_1x_2$ plane, shown in Figure 6, allows drawing conclusions about the possible machining modes of the element and choose from the acceptable modes, characterized by a minimum of energy costs [6]. Determination of the required supply value is made by nomograms, the form of which is shown in Figure 7.

4. Discussion
The obtained graphical interpretations of the functional dependencies of the microhardness and roughness on the voltage applied to the electrode, the amplitude of the vibrations of the acoustic system, the clamping pressure and supply value $R_a (U_R, A, P, S)$ using the methods of mathematical planning of the experiment allows us to simultaneously take into account several main factors determining the electroacoustic mode coating, such as: voltage applied to the electrode, amplitude of ultrasonic vibrations, supply values - which is undoubtedly promising for board search for optimal modes.

A methodology has been developed for the accelerated calculation and analytical selection of the optimal parameters of the electroacoustic coating mode based on multi-factor experimental design, which made it possible to optimize the calculation time of the basic physical and mechanical properties of the processed products. The result of solving the presented problem in the form of a program module of the predicted tribological and operational properties allows obtaining nomograms of the main modes depending on the given surface quality parameters.

Analyzing the results obtained and based on the needs of mechanical engineering in obtaining high-quality surfaces of machine parts, it is possible to give recommendations on installing the appropriate spray coating mode; the voltage applied to the electrode is $U_R = 37.5$ V, the amplitude of the vibrations of the acoustic system is $A = 10$ μm, the supply is 0.5 mm/min, the clamping pressure $S = 12.5$ N.

After checking the adequacy of the obtained dependencies using the Fisher's ratio and method for residual analysis, they can be used in the proposed methodology for optimizing the process of applying heat and wear proof coatings of machine parts in a complex acoustic field [7]. At the first stage, it is necessary to construct level surfaces for a given microhardness $HV = 7000$ according to
Vickers test and roughness $R_a = 0.63 \mu m$. At the second stage, the simultaneous solution is determined by graphically intersecting the corresponding surfaces shown in Figure 3. At the third stage, the set of solutions is determined (intersection points of the surfaces) from which those values are selected that correspond to the minimum values of the amplitude of ultrasonic vibrations and the voltage applied to the working elements of stations for applying heat and wear proof coatings for machine parts.

The above dependencies are rather complicated, therefore, the use of the obtained data in an analytical form for optimization is very difficult in real production. The acceptable variation of the main modes, the so-called working range, imposes additional restrictions on obtaining the specified surface quality parameters [8]. Therefore, the proposed optimization method should be automated at the level of the hardware-software package of a microprocessor control system based on the creation of specialized cartridges for the corresponding materials and electrodes.

5. Conclusions

As a result of theoretical and experimental research, there was developed an autoprocessing module of the automated control system of an electroacoustic spray coating station for multifunctional heat and wear proof coatings of machine parts of a screw for a combine harvester using electroacoustic spraying. A structural scheme was developed, a generalized model and methodology to optimize the process of applying a heat and wear resistant protective coating for parts of agricultural machinery, that work in difficult operating conditions, were proposed [9]. The margin of error for the obtained mathematical models of the dependencies of microhardness and roughness on the main coating modes does not exceed 7%, which indicates the fine reproducibility of the results. The proposed optimization technique according to the criterion of reduced costs will allow not only reducing the electrical energy consumption of the technological process, but also to increase the operating life of the executive equipment of the electroacoustic application of heat and wear proof coatings, which ultimately will reduce operating costs by 20%. The versatility of the method, low cost of applying multifunctional coatings, and ease of implementation with the possibility of recycling hard alloys make this technology economically attractive compared to the current methods and technologies [10].

This technology of applying heat and wear proof coatings by electroacoustic spraying in a complex ultrasonic field conducted by means of a longitudinal-torsional acoustic waveguide allows using the effect of vectored ultrasonic vibrations when forming rheological properties of conductive heat and wear proof coatings with an amorphous structure, which gives unique operational properties.

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