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# DETERMINATION OF CHARACTERISTICS OF THE CONSTRUCTION MACHINE BLADE ION-PLASMA COATING

*Determination of characteristics of the construction machine blade ion-plasma coating. Using the theory of the design of experiments, the values of the characteristics of the ion-plasma coating applied to the surface of the construction machine cutting elements to minimize wear are established. The parameters of optimization are the hardness, the roughness of the substrate, and the thickness of the applied coating. It is determined that the hardness of 50 HRC, the coating thickness of 4 μm and the substrate roughness of 0.32 μm cause the minimum wear of the cutting elements of a motor grader working unit. These values of the characteristics are confirmed during a field experiment on a motor grader.*

*Визначення характеристик іонно-плазмового покриття ножа будівельної машини*

*За допомогою теорії планування експериментів встановлені значення характеристик іонно-плазмового покриття, що наноситься на поверхню ріжучих елементів будівельної машини для мінімізації зносу. Параметри оптимізації - твердість, шорсткість підкладки і товщина нанесеного покриття. Встановлено, що твердість 50 HRC, товщина покриття 4 мкм і шорсткість підкладки 0,32 мкм викликають мінімальний знос ріжучих елементів робочого органу автогрейдера. Ці значення характеристик підтверджені під час польового експерименту на автогрейдері.*

*Определение характеристик ионно-плазменного покрытия ножа строительной машины*

*С помощью теории планирования экспериментов установлены значения характеристик ионно-плазменного покрытия, нанесенного на поверхность режущих элементов строительной машины для минимизации износа. Параметры оптимизации - твердость, шероховатость подложки и толщина нанесенного покрытия. Установлено, что твердость 50 HRC, толщина покрытия 4 мкм и шероховатость подложки 0,32 мкм вызывают минимальный износ режущих элементов рабочего органа автогрейдера. Эти значения характеристик подтверждены во время полевого эксперимента на*

*автогрейдере.*

**Introduction.** To determine the parameters of the ion-plasma coating, which is applied to the surface of a construction machine working unit and ensures its minimal wear, we use the theory of the design of experiments [1].

It is well known that good adhesion of the coating to the base metal is guaranteed by the composition of the applied coating, the roughness and the hardness of the material of the surface to be coated as well as its thickness. The values of these parameters are rationally chosen.

For our studies, as an example of optimization, we chose a motor grader with the working unit (blade) made of 65G (65Г) steel.

Hardness is chosen as one of the parameters due to the fact that it is rather easily determined at any point of the motor grader blade without causing any damage before and after operation.

As the results of the studies [2] show, the value of the roughness of the surface to be coated should be 0.16 Ra minimum. Otherwise, the applied coating will gradually peel off due to poor adhesion to the substrate. In this regard, one of the main tasks is to determine the rational roughness of the surface to be treated, which would ensure the best adhesion of the coating to the basic metal.

**Purpose and problem setting.** The purpose of this work is to determine the conditions for applying the ion-plasma coating to minimize the wear of a motor grader cutting unit (blade).

**Investigation of the dependence of wear resistance on the parameters of the ion-plasma coating.** The thickness of the coating varies within the range of 3-7 micrometers as the thickness of 3-6 micrometers provides the best adhesion bonds with the basic metal; the thickness of less than 3 micrometers does not significantly affect the physical and mechanical properties of the unit [2]. The coating thickness of more than 6 micrometers has insufficient adhesion that ultimately leads to peeling off the substrate.

As the value of hardness can be an integer only, we conducted four series of experiments, setting the hardness values of 40, 45, 50, 55.

Based on the theory of the mathematical design of experiments [3-5], the variable factors are the thickness and roughness of the coating, designated as $X_1$ and $X_2$ respectively. In this case, wear is the response function denoted as Y.

So, the above mentioned statements stipulate the range of the boundaries of the factors $X_{1min} = 3$; $X_{2max} = 7$; $X_{2min} = 0.16$; $X_{2max} = 0.48$. Then the intervals of factor variation will be respectively:

$$\Delta X_1 = X_{2\max} - X_{1\min} = 4;$$
$$\Delta X_2 = X_{2\max} - X_{2\min} = 0.32.$$

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First of all, a factorial experiment of the first order is carried out. The purpose of this experiment is to find a mathematical model of the dependence of Y on $X_1$, $X_2$, which can be presented as a linear polynom. To achieve this goal, a full factorial experiment of type $2^n$ is conducted for each value of hardness. The results of this experiment are given in Tables 1-4.

Table 1 – Values of coating thickness, roughness and wear with substrate hardness of 40 HRC

| № of test | $X_1$ | $X_2$ | Y |
|---|---|---|---|
| 1 | 3 | 0.16 | 0.3540 |
| 2 | 3 | 0.48 | 0.6723 |
| 3 | 7 | 0.16 | 0.7012 |
| 4 | 7 | 0.48 | 0.6822 |

Table 2 – Values of coating thickness, roughness and wear with substrate hardness of 45 HRC

| № of test | $X_1$ | $X_2$ | Y |
|---|---|---|---|
| 1 | 3 | 0.16 | 0.2421 |
| 2 | 3 | 0.48 | 0.6253 |
| 3 | 7 | 0.16 | 0.6643 |
| 4 | 7 | 0.48 | 0.6211 |

Table 3 – Values of coating thickness, roughness and wear with substrate hardness of 50 HRC

| № of test | $X_1$ | $X_2$ | Y |
|---|---|---|---|
| 1 | 3 | 0.16 | 0.2632 |
| 2 | 3 | 0.48 | 0.6133 |
| 3 | 7 | 0.16 | 0.6311 |
| 4 | 7 | 0.48 | 0.5722 |

Table 4 – Values of coating thickness, roughness and wear with substrate hardness of 55 HRC

| № of test | $X_1$ | $X_2$ | Y |
|---|---|---|---|
| 1 | 3 | 0.16 | 0.2332 |
| 2 | 3 | 0.48 | 0.6318 |
| 3 | 7 | 0.16 | 0.6511 |
| 4 | 7 | 0.48 | 0.5987 |

Note: for each row of the plans of Tables 1-4, two tests for wear of the motor grader blades are carried out on a special laboratory bench [6, 7]. Upon that, the average values are recorded in the tables as the value of Y.

Further, for all tables 1-4, the regression equation is calculated:

$$\hat{Y} = b_0 + b_1 X_1 + b_2 X_2. \quad (1)$$

The results of calculating its coefficients are presented in Table 5.

Table 5 – Value of regression coefficients

| Value of hardness | $b_0$ | $b_1$ | $b_2$ |
|---|---|---|---|
| 40 | 0.230 | 0.045 | 0.468 |
| 45 | 0.107 | 0.052 | 0.531 |
| 50 | 0.170 | 0.041 | 0.455 |
| 55 | 0.114 | 0.048 | 0.543 |

According to the Fisher's ratio test, the adequacy of the obtained equations is verified by comparing the calculated Fisher's ratio test $F_P$ with the tabulated $F_T$ at a significance level of q = 0.05. As all the cases under consideration indicate that $F_P > F_T$, it can be concluded that the equations are not adequate. In the end, it is decided to continue the experiments. With that, the received plans $2^n$ are supplemented up to the central compositional plans of the second order.

Then the regression equation is calculated:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + b_{11} X_1^2 + b_{12} X_1 X_2 + b_{22} X_2^2. \quad (2)$$

The results of calculating the regression coefficients are given in Table 6.

Table 6 – Values of the coefficients of the linear regression equation

| Value of hardness | Value of regression coefficients | | | | | |
|---|---|---|---|---|---|---|
| | $b_0$ | $b_1$ | $b_2$ | $b_{11}$ | $b_{12}$ | $b_{22}$ |
| 40 | 0.806 | -0.169 | -1.493 | 0.032 | -0.264 | 4.917 |
| 45 | 0.108 | -0.155 | 2.715 | -0.033 | -0.333 | -0.779 |
| 50 | 0.868 | -0.202 | -2.068 | 0.037 | -0.320 | 6.137 |
| 55 | 0.172 | -0.170 | 2.239 | 0.035 | -0.352 | 0.116 |

For each value of the hardness of the substrate, the graphical presentation of the response surface is shown in Fig. 1-4.

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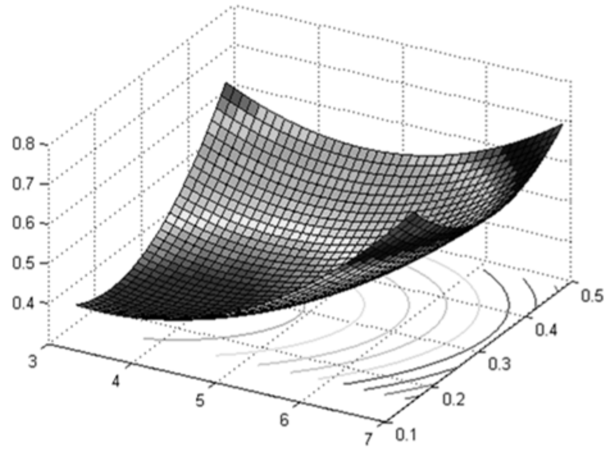


Figure 1 – Response surface for hardness of 40 HRC

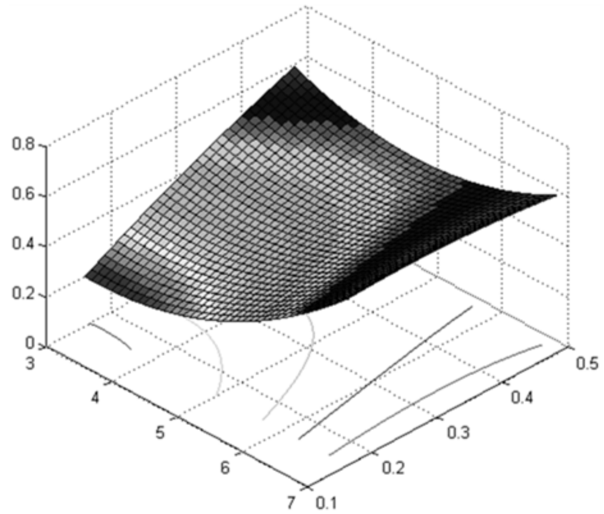


Figure 2 – Response surface for hardness of 45 HRC

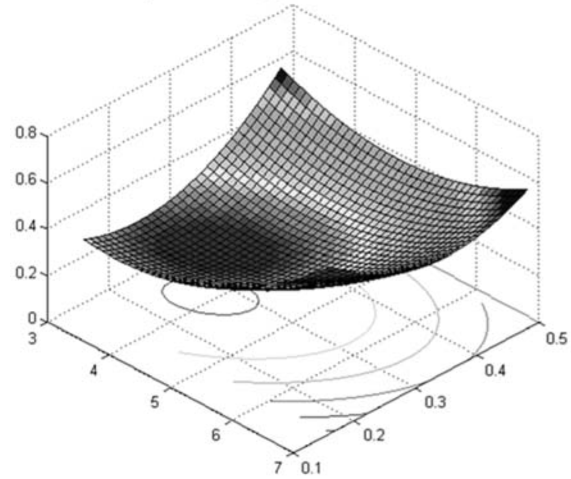


Figure 3 – Response surface for hardness of 50 HRC

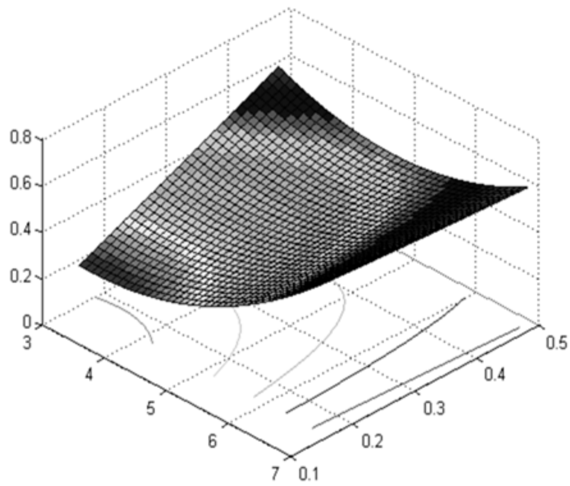


Figure 4 – Response surface for hardness 55 of HRC

Then the minimum value of function Y in the domain is found

$$\begin{cases} 3 \le X_1 \le 7 \\ 0.16 \le X_2 \le 0.48 \end{cases} \quad (3)$$

As is known from [5], this value can be taken either at the boundary of the domain or at a stationary point. The coordinates ( $X_1^0$ , $X_2^0$ ) of the stationary point are determined as a result of solving the system of equations

$$\begin{cases} \dfrac{\partial Y}{\partial X_1} = 0 \\ \dfrac{\partial Y}{\partial X_2} = 0 \end{cases},$$

In our case, this system of equations has the form

$$\begin{cases} b_1 + b_{12} X_2 + 2 b_{11} X_1 = 0 \\ b_2 + b_{12} X_1 + 2 b_{22} X_2 = 0 \end{cases} \quad (4)$$

We solve the above-mentioned system of equations (4) by formulas

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$$X_1^0 = \frac{-2b_{22}b_1 + b_2 b_{12}}{4b_{11}b_{22} - b_{12}^2},$$

$$X_2^0 = \frac{-2b_{11}b_2 + b_{12}b_1}{4b_{11}b_{22} - b_{12}^2}.$$

The obtained values of the coordinates of the stationary point are given in Table 7.

Table 7 – Values of the stationary point coordinates

| Value of hardness | Coordinates of the stationary point | |
|---|---|---|
| T | $X_1^0$ | $X_2^0$ |
| 40 | 3.689 | 0.251 |
| 45 | 5.38 | 0.592 |
| 50 | 3.947 | 0.271 |
| 55 | 6.947 | 0.9 |

As can be seen from the presented table, only in two cases (at T = 40 and T = 45) the stationary points ($X_1^0 = 3.69$; $X_2^0 = 0.25$ and $X_1^0 = 3.95$; $X_2^0 = 0.27$) belong to the domain of determining the factors. As to the rest of cases, the minimum value of function Y is observed at the boundary (3). Having inserted all the necessary values and having solved the regression equation (2), we determine the minimum value of the function in each case. The coordinates of the extreme point and the value of Y are given in Table 8.

As can be seen from this table, the minimum value of wear is expected with the hardness of 50 HRC, the thickness of coating of 4 μm and the roughness of 0.27 μm. However, since the nearest possible values of roughness are only 0.16 and 0.32 μm, two additional experiments are carried out, the results of which are given in Table 9.

Table 8 – Values of response at the extreme point

| Value of hardness | Coordinates of the extreme point | | Response value |
|---|---|---|---|
| | $X_1$ | $X_2$ | Y |
| 40 | 3.7 | 0.25 | 0.307 |
| 50 | 4.0 | 0.27 | 0.189 |

Table 9 – Coating thickness, roughness and wear with substrate hardness of 50 HRC

| Value of hardness | Value of parameters | | Value of wear |
|---|---|---|---|
| | $X_1$ | $X_2$ | Y |
| 50 | 4.0 | 0.16 | 0.175 |
| | 4.0 | 0.32 | 0.148 |

As can be seen from Table 9, the values of parameters received with the use of the theory of the design are indeed the most acceptable. The minimum value of wear is received with the hardness of 50 HRC, the coating thickness of 4 μm and the roughness of 0.32 μm.

Thus, the results of the experiment to research the wear of the motor-grader blades with the ion-plasma coating at different values of the hardness of the substrate material, the surface roughness and the coating thickness confirm the reliability of the calculations obtained using the theory of the design of experiments. The above characteristics of the ion-plasma coating can be used for other construction machines.

## Conclusions

The theory of the design of experiments is used to determine the values of the parameters of the applied coating on the surface of the cutting elements. In this case, the hardness, the roughness of the substrate and the thickness of the applied coating are taken as parameters of optimization.

With the value of the hardness of 50 HRC, the coating thickness of 4 μm and the substrate roughness of 0.32 μm, the wear of the cutting elements of the motor grader working units is minimal.

Using the theory of the design of experiments proposed above, it is possible to determine the most acceptable parameters of the ion-plasma coating for any working units of construction machines.

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