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Fractal study of the effect of ion plasma coatings on wear resistance

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The feasibility of using the fractal approach to assess the effect of plasma coatings on increasing the wear resistance of parts was studied. Using the experimental design theory, a relationship has been established between the rigidity of the base material of the substrate, the roughness of the surface on which the coating is applied, the thickness of the coating and wear. The studies were carried out on parts of a volumetric hydraulic drive made of steel 38X2MYA after heat treatment. Ti–Cr–N ion plasma coatings were applied to the working surfaces. To assess the effect of the Ti–Cr–N coating structure on its wear indicators, fractal analysis was used. The lowest wear value was obtained for samples with a hardness of the base material of 45 HRC, its roughness of 0.16 and a coating thickness of 6 microns. The results of studies of wear indicators of parts with Ti–Cr–N coating showed the feasibility of using a fractal approach.

Keywords: ion-plasma, surface, fractal, hardening, model, ion-plasma, coatings.

Фрактальне дослідження впливу іонно-плазмових покриттів на зносостійкість. *Д.Б.Глушкова, В.М.Волчук*

Проведено дослідження доцільності використання фрактального підходу для оцінки впливу плазмових покриттів на підвищення зносостійкості деталей. За допомогою теорії планування експерименту встановлено зв'язок між товщиною покриття і жорсткістю основного матеріалу підкладки, шорсткістю поверхні, на яку наноситься покриття, та его зносом. Дослідження проводилися на деталях об'ємного гідроприводу, виготовлених із сталі 38Х2МЮА після термічної обробки. На робочі поверхні наносилися іонно-плазмові покриття Ti–Cr–N. Для оцінки впливу структури покриття Ti–Cr–N робочої поверхні деталей об'ємного гідроприводу на показники його зношування застосовували фрактальний аналіз. Встановлено, що найменше значення зносу отримано при жорсткості основного матеріалу HRC 45, його шорсткості 0,16 і товщині покриття 6 мкм. Результати проведених досліджень показників зношування деталей з покриттям Ti–Cr–N показали доцільність застосування фрактального підходу.

1. Introduction

The structure and properties of many materials are influenced by methods of their preparation, processing modes, phase and chemical composition, etc. [1–4].

The application of titanium nitride coatings on the parts of the volumetric hydraulic drive influenced on the tribotechnical characteristics: wear resistance increased, friction coefficient decreased. But the efficiency of these critical parts depends on durability, which in this case involves reducing or neutralizing the danger of surface hardening, as well as on such an important indicator as corrosion resistance [5–8]. Based on the analysis of works devoted to the use of plasma coatings [9–12], the Ti–Cr–N coating system with preliminary ion bombardment of the surface with chromium was chosen. Cr was chosen as the material for ion bombardment, since it makes it possible to reduce the temperature of the substrate before applying the coating and avoid the risk of surface softening. The ion bombardment increases the density of nucleation centers, reduces the number of vacancies and pores, and introduces thermal energy directly into the surface zone, stimulating diffusion processes. For each temperature and coating type, there are optimal ion bombardment modes that provide the most perfect structure. The ion bombardment leads to a decrease in grain size, which contributes to the formation of nanocrystalline films. The grain size can be controlled by adjusting the energy and flux density of the bombarded ions. It is known that the best combination of strength and plastic properties occurs when the grain size is less than 10 nm [13].

The purpose of the work is to study the feasibility of using a fractal approach to evaluate the effect of plasma coatings on increasing the wear resistance of parts of a volumetric hydraulic drive. Fractal analysis has successfully proven itself for modeling the structure and properties of many materials [14–18].

Based on the above, the purpose of this work is to apply fractal formalism to estimate the non-uniform structure of a metal surface after ion-plasma treatment, followed by establishing the relation between the structure dimension spectrum and the mechanical properties of the metal. To achieve this objective, the following tasks have been implemented:

1. Investigate the effect of ion-plasma treatment on the nature of wear damage to the applied coatings.
2. Apply multifractal analysis of the heterogeneous structure to evaluate the mechanical properties of metal surfaces after ion-plasma treatment.

2. Experimental

To apply the Ti–Cr–N coating on the surface of the 38X2MYA steel, the installation chamber was modified (Fig. 1).

In the center of the vacuum chamber, a cylinder course 2 is mounted with parts on which the coating 3 is applied. On the side flanges of the vacuum chamber, plasma sources 3 with metal cathodes 4, 5, 6 are placed. One of the plasma sources (cathode 4) evaporated Ti, and the remaining two — Cr. The course radius adjusts the distance from the parts to the evaporators. This distance may vary depending on the size of the installation chamber. During rotation of the sprayed surface, the parts pass alternately under the active cathodes 4, 5, 6. The deposited coating depends on the distance from the part to the evaporator, speed of rotation of the course, number of evaporators, and material of the cathodes. The choice of these parameters in each specific case is important since when three cathodes operate simultaneously, there are areas where there is no condensation of the direct flow of the substance, where the condensation of the evaporated substance by only one evaporator occurs, and areas where the flows from two evaporators overlap.

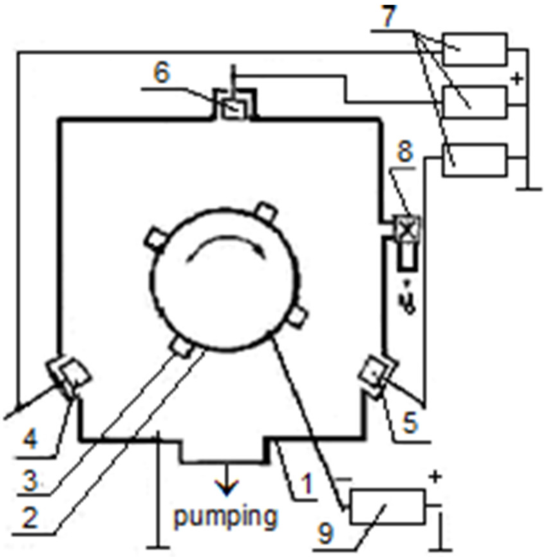


Fig. 1. Scheme of a vacuum chamber for deposition of coatings from double nitride systems. *1* — vacuum chamber; *2* — cylinder course; *3* — parts; *4*, *5*, *6* — cathodes; *7* — welding rectifiers; *8* — pressure device; *9* — negative voltage source.

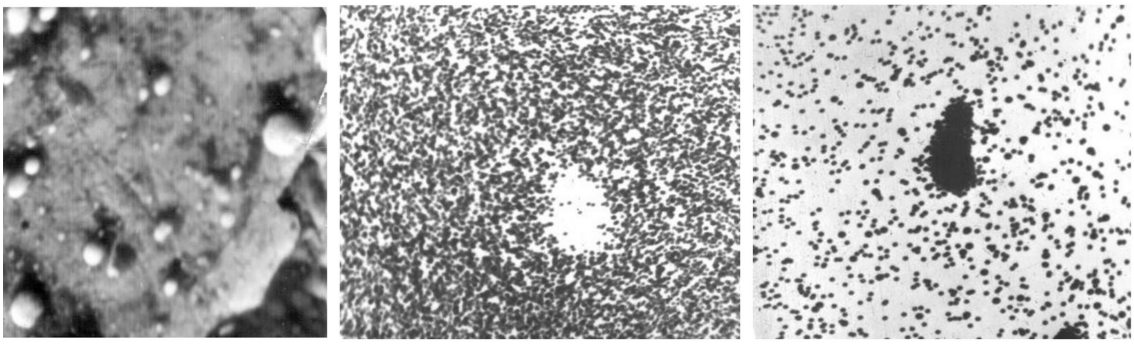
The angular size of these areas depends on the ratio between the radius of the course (r) and the radius of the "Bulat" installation chamber (R). For our operating conditions, the following ratio was chosen: $r/R = 0.6$. The rotation speed of the course with sprayed parts was 10 rpm during the operation of the three evaporators. The device received a positive decision on Application No. 2010 03834 dated 02.04.2010. BT-1 titanium, chromium, and nitrogen (99.97 %) were used as cathode materials.

Fig. 2 shows the structure of the studied material.

The optimal modes of the Ti–Cr–N coating deposition on the working surfaces of

Table 1. Optimal modes of deposition of Ti–Cr–N coatings on working surfaces of volumetric hydraulic drive parts

Emission cathode material	Arc current, I_1, A	Arc current, I_2, A	Voltage U, V	Current I, A	Pressure P, torr	Time t, min
Stage 1: purification, heating and activation with chromium ions						
Chrome	80	–	900	2	$1{\cdot}10^{-4}$	7
Stage 2: spraying the coating layer in an atmosphere of nitrogen or nitrogen-containing gas						
2 cathodes: 1st — chrome, 2nd – titanium	80	70	150	3	$5cdotБ\%\%\%Ax$ 10^{1963}	25



×3500 *a* ×3500 *b* ×3500 *c*

Fig. 2. Images of a Ti–Cr–N coating. a — general view of the coating; b — nature of Cr distribution in the coating in characteristic Cr rays; c — nature of Ti distribution in the coating in the characteristic Ti rays.

volumetric hydraulic drive parts are shown in Table 1.

Fractal analysis was used to assess the effect of the Ti–Cr–N coating structure on its wear indicators.

3. Results and discussion

It is known that not only the composition of the applied coating is of great importance, but also such parameters as the hardness of the substrate material, roughness of the surface on which the coating is deposited, and thickness of the coating. The hardness is chosen as one of the indicators, since it is easily tested at any point of the product without affecting its integrity both before and after operation. The practice of using steel products with plasma coatings has shown that the roughness of the surface on which the coating is deposited should be at least 0.48 R_a. Otherwise, peeling of the coating is observed due to poor adhesion to the substrate. The research material was steel 38X2MUA; heat treatment provided the best ratio of strength and plastic properties.

After heat treatment, the hardness of 38X2MYA steel ranges from 40 to 45 HRC. The thickness of the applied coating varied from 3 to 6 microns to provide a good adhesion; a smaller thickness does not significantly affect the properties of the product, and in the case of a thickness of more than 6 microns, peeling is observed due to poor adhesion to the substrate. According to the methods of mathematical planning of the experiment, we take the coating thickness and roughness as a variable factor, and denote them X_1 and X_2. As a response function, we accept wear and denote Y. Based on the above considerations, we assume that the limits of the existence (change) of the factors are $X_{1min} = 3$; $X_{1max} = 6$; $X_{2min} = 0.10$; $X_{2max} = 0.48$. Fluctuation intervals of the factors, respectively $\Delta X_1 = 6 - 3 = 3$; $\Delta X_2 = 0.48 - 0.1 = 0.38$.

First, a factorial experiment of the first order was conducted, the purpose of which was to obtain a mathematical model of the dependence Y on X_1 and X_2 in the form of a linear polynomial. For this, a full factorial type experiment was implemented (for each hardness value) 2^n.

Table 2. The lowest values of wear indicators in the range from 42 to 46 HRC

Hardness, HRC	arguments		function	
	X_1	X_2	D	Y
42	6	0.10	1.90	3.30
43	6	0.10	1.87	4.00
44	6	0.10	1.91	3.60
45	6	0.15	1.94	2.11
46	6	0.10	1.90	3.00

The fractal dimension was calculated using the Hausdorff method [13]. Photos of the structure were processed in a 256-color format with shades of gray. To calculate D (1) fractal dimension values, the structure photo was covered with cells N, size l. of which changed from 2 to 9 pixels.

$$D = -\lim_{\delta \to 0} \frac{\ln N(l)}{\ln l}. \qquad (1)$$

An example of fractal 3D analysis for a structure in Fig. 2A is shown below (Fig. 3).

Based on the results of processing the experimental values, the linear models for predicting wear indicators (2)–(6) were obtained.

At 42 HRC:

$$Y_1 = 10.71 - 0.98 \cdot x_1 + 2.27 \cdot x_2 - - 0.88 \cdot DR^2 = 0.96 . \qquad (2)$$

At 43 HRC:

$$Y_2 = 11.65 - 0.80 \cdot x_1 + 1.48 \cdot x_2 - - 1.69 \cdot D, \quad R^2 = 0.95 . \qquad (3)$$

At 44 HRC:

$$Y_3 = 13.04 - 0.60 \cdot x_1 + 1.25 \cdot x_2 - - 3.14 \cdot D, \quad R^2 = 0.98 . \qquad (4)$$

At 45 HRC:

$$Y_4 = 17.64 - 0.12 \cdot x_1 + 0.16 \cdot x_2 - - 7.73 \cdot D, \quad R^2 = 0.89 . \qquad (5)$$

At 46 HRC:

$$Y_5 = 5.95 - 0.44 \cdot x_1 + 0.95 \cdot x_2 - - 0.16 \cdot D, \quad R^2 = 0.98 . \qquad (6)$$

The relative error in calculating wear indicators ranged from 0.04 to 8.96.

After performing a direct calculation, we find the lowest wear value in each case. Table 2 shows data for the lowest values of Y wear.

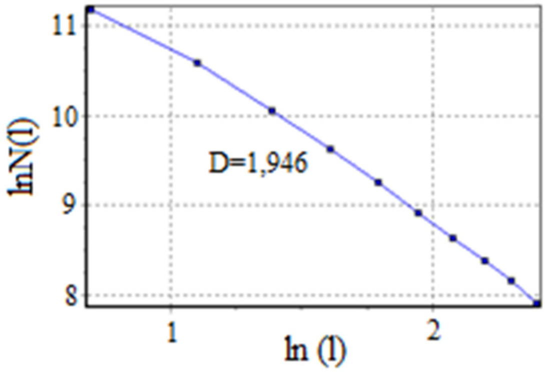


Fig. 3. Bilogarithmic dependence of cells covering an object on its size.

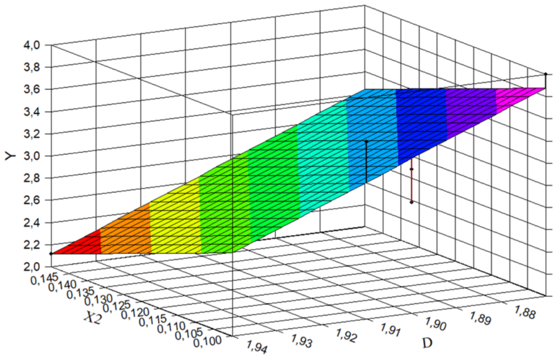


Fig. 4. Assessment of surface roughness and fractal dimension effect on wear indicators.

As can be seen from this table, the lowest wear value of 2.11 is predicted at a hardness of 45, coating thickness of 6, and roughness of 0.15.

Response surface (Fig. 4) and model for assessing the lowest wear values at a given point $X_1 = 6$ (7) are below:

$$Y = 35.28 - 12.80 \cdot X_2 - 16.11 \cdot D, \quad R^2 = 0.84 . \qquad (7)$$

The correlation coefficient of $Y(X_2)$ model without using indicators of the surface fractal dimension was only 0.73 (8):

$$Y = 27.30 - 6.20 \cdot D, \quad R^2 = 0.63. \qquad (8)$$

To confirm this hypothesis, an experiment to determine wear resistance at a hardness of 45, roughness of 0.16, and coating thickness of 6 was conducted.

4. Conclusion

The research has been carried out on the possibility of using a fractal approach to assess the effect of plasma coatings on increasing the wear resistance of parts of a volumetric hydraulic drive. Using the experiment planning method, it was established that the lowest value of wear of a part made of 38X2MUA steel after heat treatment was obtained with a hardness of the base material of 45 HRC, its roughness of 0.15 and a coating thickness of 6 microns.

A fractal analysis of the Ti–Cr–N coating, characterized by the presence of Ti and Cr droplets, some of which are located on the surface, and some of which are fixed in the volume of the coating, was carried out. The fractal dimension was calculated using the Hausdorff cell method.

To assess the wear resistance of parts of a volumetric hydraulic drive, a fractal model with a correlation coefficient of 0.84 was obtained; and for a model using only roughness indicators of the base material, the correlation coefficient is lower and amounts to 0.73 (9) at fixed coating thicknesses of 6 μm, which indicates the advisability of using fractals.

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