ISSN 2079-1372 Problems of Tribology, V. 30, No 2/116-2025, 77-83

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2025-116-2-77-83

Optimization of discrete structure of electrospark coatings

V. Antonyuk[1] 0000-0003-0690-2411, **L. Lopata**[*2] 0000-0002-2053-9252

[1]*National Technical University of Ukraine "Igor Sikorsky, Polytechnic Institute", Kyiv, Ukraine*
[2]*G. S. Pisarenko Institute for Problems of Strength of National Academy of Sciences of Ukraine*
**E-mail: beryuza@ukr.net*

Received: 10 May 2025: Revised 29 May 2025: Accept: 14 June 2025

Abstract

The presented article considers the disadvantages of chromium coatings and shows the possibility of their elimination by obtaining coatings of discrete structure. The principle of coatings of discrete structure allows to organically combine physical processes underlying pulse hardening methods with a discrete structure determining their service properties. It is shown and substantiated that the method of electric spark alloying is the most suitable for applying discrete coatings, since this process is discrete by its nature. The advantage of discrete coatings is the absence of a softening effect when a brittle crack passes from the coating to the base metal due to excessively high adhesive strength. High cohesive and adhesive resistance of individual discrete sections of the coating is achieved by limiting normal stresses in the coating and tangential stresses in the plane of adhesive contact with the base by changing the size and shape of an individual section. This article is devoted to determining the optimal parameters of a discrete structure. The required coating design is determined by a calculation method based on a model that describes the stress-strain state of the coating.

Keywords: chromium plating, spark alloying, discrete coating, stress-strain state, cohesive and adhesive strength, thermomechanical resistance, coating continuity, wear

Introduction

In increasing the durability of special equipment parts, priority is given to hardening coatings on the inner surface of the parts. However, most coatings are destroyed during operation, which is associated with insufficient adhesive and cohesive strength, the occurrence and development of a network of cracks and the weakening of the coating during operation. Argon-arc surface hardening is considered as an alternative to coatings for hardening the inner surface of special equipment parts [1]. In research and industrial practice, chromium coatings applied by the electrolytic method are most common for increasing the durability of special equipment parts. However, with sufficient erosion-corrosion resistance of the Cr coating, it is not possible to eliminate cracking and peeling [2]. Most studies are devoted to improving the application technology and eliminating the disadvantages of Cr coatings**.**

The aim of the work

Increasing the durability and bearing capacity of coatings by using a discrete structure.

Research results and discussion

The main disadvantages of chromium coatings include brittleness at temperatures $T<(0,1\ldots0,2)T_{пл}$ and extreme sensitivity to interstitial impurities both during its application and during operation. As a consequence, there is low resistance to mechanical and thermal shocks.

One of the disadvantages of electrolytic coatings is hydrogenation of the surface layer of the part. This leads to the phenomenon of hydrogen embrittlement and hydrogen corrosion. As a consequence, there is a decrease in the strength and ductility of the part. Thus, the fatigue limit of steels can decrease by 50% [3].

Therefore, along with the problems associated with the development and use of galvanic coatings, there is a need to assess the effect of coatings on reducing the strength and ductility of the base material. It is noted [4] that the most sensitive characteristic is the relative narrowing ψ. Electrolytic Cr coating leads to a decrease in ψ by 1.4 times. Heat treatment at 200^0C promotes a slight increase in ψ from 33 to 39% (for the original sample without coating $\psi = 45\%$). This is explained by the removal of hydrogen from the coating during heat treatment.

Technological difficulties in chroming are associated with the impossibility of maintaining a ratio between the anode and cathode areas, in which the former would exceed the latter, as well as the unequal resistance of the electrolyte along the length of the barrel inside the channel [5].

Another important circumstance in chroming the barrel bore is the need to ensure a uniform coating thickness along the entire length of the barrel. For rifled barrels, it is difficult to achieve a uniform Cr coating and high adhesive strength in the area of the mating of the lands and rifling. To eliminate these shortcomings, a number of technological methods are used to improve the dissipation capacity of the electrolyte, including current "push". To ensure a high-quality Cr coating, it is necessary to strictly control the composition of the electrolyte, its temperature and current density. A temperature deviation of $2\ldots3^0$C leads to a significant change in the properties of Cr deposits. The presence of chemically active products in the gas environment, in particular nitrogen and its compounds, leads to the formation of brittle compounds. This leads to cracking and peeling of coatings under the influence of thermomechanical loads. Therefore, one of the ways to increase the durability and stability of chromium coatings is to alloy them with elements such as V, Nb, Mo, Ni and other elements.

The most effective materials for protection against thermomechanical wear are Ni and W. Alloying with Ni (0.1...0.3%) leads to an increase in the plasticity of the coatings, to a decrease in carbon deposits and a network of cracks during operation [6]. Alloying of Cr coatings is carried out by introducing alloying additives into the electrolyte. Thus, electrodeposition of Cr-Ni alloy is carried out from a diluted chromium plating electrolyte containing additives of nickel salts. However, simultaneous electrodeposition of Cr with other metals in practice is associated with great technological difficulties. Continuous monitoring and stabilization of the electrolysis process in terms of current, concentration and temperature of the electrolyte and other parameters are necessary [5,7]. In the search for ways to improve the properties of electrolytic Cr coating, a trend has emerged for multi-stage application: the use of additional electrospark alloying (ESA) treatment after electrodeposition.

The use of the ESA method without a continuous corrosion-resistant sublayer does not provide positive results [8]. Therefore, in the works [7, 9], the ESA method was used on pre-electrodeposited high-density Cr and NiCr alloys that protect the steel base from high-temperature gas corrosion.

Research results and discussion

The ESA method is used to apply wear-resistant materials: hard alloys, W + Co, Ni-W-Co, etc. [7, 9]. The ESA method is most suitable for the task of strengthening the internal surfaces of special equipment parts.

The ESA method uses serial industrial equipment.

ESA treatment increased the wear resistance and durability of special equipment parts by 2 times according to the results of operational tests in comparison with standard chrome plating [9].

The mechanism of destruction of the Cr coating and the electric spark coating during operation is associated with the formation and development of a network of regular cracks, their merging and subsequent chipping of sections of the coatings [7]. This circumstance was the basis for the creation of the principle of discrete coatings with increased thermomechanical resistance [10, 11]. The discrete coating consists of individual sections, the dimensions of which are similar to the network of regular cracks in a continuous coating. The formation of a network of regular cracks occurs as a phenomenon of self-regulation and a decrease in the level of the stress-strain state of the coating. The discrete structure of the coating (applied from the same material as the continuous coating with equal thicknesses) allows for a multiple increase in the load-bearing capacity of the coated part, especially in the area of high loads and deformations of the base material [11]. High cohesive and adhesive resistance of individual discrete sections of the coating is achieved by limiting normal stresses in the coating and tangential stresses in the plane of adhesive contact with the base by changing the size and shape of an individual section.

The ESA method is the most suitable for applying discrete coatings, since ESA is discrete by nature. A single electric discharge ensures stability of the dimensions and properties of an individual discrete section of the coating. By changing the pulse frequency or the speed of relative movement of the electrode and the part, it is possible to regulate the number of discrete sections on the working surface of the part, as well as the continuity of the coating. The discrete structure of the coating allows (unlike the traditional continuous coating) to successfully apply surface plastic deformation (SPD). The use of SPD for continuous coatings is impossible due to their cracking and peeling. Discrete coatings can combine ESA and SPD in one technological cycle. In this case, SPD is the final dimensional processing and ensures the required surface purity of the discrete coating. Continuous coatings applied by the ELA method require final mechanical processing due to their high roughness.

When applying a discrete coating in one pass of the electrode, the productivity of the ESA method increases many times. The advantage of discrete coatings also lies in the absence of a softening effect when a brittle crack passes from the coating to the base metal due to excessively high adhesive strength. In [12], a criterion relationship for adhesive strength and the need to optimize it under the condition of crack transition from the coating to the base were established. The negative role of excessively high adhesive strength is confirmed by such a wear mechanism during operation as the detachment of Cr coating particles with the tearing out of metal from deep layers [8]. This article is devoted to determining the optimal parameters of a discrete structure. The required coating design can be determined by a calculation method based on a model that describes the stress-strain state of a continuous coating [13]. We select the size of the discrete section based on the regular step of the crack that occurs due to cohesive cracking of the coating.

The criterion for selecting the parameters of the discrete structure is the minimum stress level during operation, on which the wear resistance of the part surface depends. Total effective stress value in the coating:

$$\sigma_c^{ef} = \sigma_c^{op} + \sigma_c^{r} \tag{1}$$

where: $\sigma_c^{op} = \sigma_c^{m} + \sigma_c^{t}$ - operational stresses in the coating;

σ_c^{m} - stress in the coating from mechanical load;

σ_c^{t} - stress in the coating under the influence of temperature gradient;

σ_c^{r} - residual (technological) stresses in the coating.

The stresses in the coating from the mechanical load are determined from the dependence [13]:

$$\sigma_c^{m} = \frac{1}{h_c} \cdot \frac{\varepsilon_{crit}}{\left(\dfrac{1}{E_c h_c} + \dfrac{1}{E_b H_b}\right)} \cdot \left[1 - \frac{ch(ky)}{ch(kl)}\right] \tag{2}$$

where: ε_{crit} - critical deformation of the base, above which cohesive cracking of the coating begins;
H_b, h_c - thickness of the base and coating respectively;
E_b, E_c - elastic moduli of the base and coating; l - base size;
k - a coefficient that depends on the ratio of the elastic properties of the base and the coating:

$$k^2 = 2\frac{G_b G_c}{G_b h_c + G_c H_b}\left(\frac{1}{E_c h_c} + \frac{1}{E_b H_b}\right) \tag{3}$$

where: G_b, Gc - shear moduli of the coating and base.

The nature of the stress distribution in a discrete section of the coating with a length of $2l$ is shown in Fig. 1.

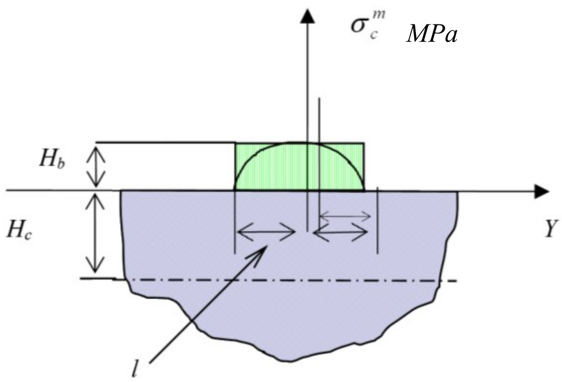


Fig. 1. Distribution of stresses σ_c^{m} along the length of the coating

The stress σ_c^{m} under the action of a temperature gradient in different variants of Cr coating for shooting conditions are given in [14]. Residual stresses in the coating σ_c^{r} were determined by the radius of curvature of a flat sample after coating application. Using the method for calculating thin plates for bending, we determine σ_c^{r} :

$$\sigma_c^{r} = \frac{4E_b H_b^3}{6(1-\mu^2)(H_b + h_c)R h_c} \tag{4}$$

where: μ - base material coefficient; R – radius of curvature of the sample.

In a linear stress state and $h_c << H_b$, dependence (4) turns into the well-known Stoney formula [15]:

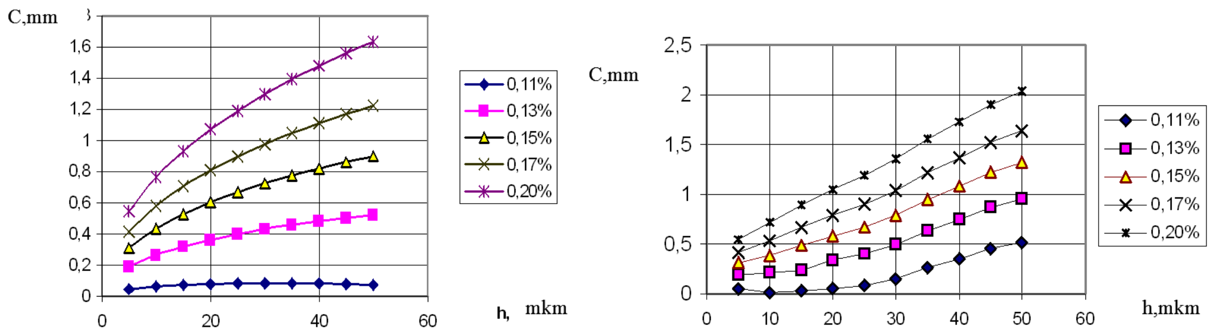
$$\sigma_c^r = \frac{E_b H_b^2}{6Rhc} \tag{5}$$

Since we assume that the cohesive strength of the coating $\sigma_c^{coh} = \varepsilon_{crit} E_c$ is distributed according to the normal law with a standard deviation of $0.1\,\sigma_c^{coh}$, then the crack is most likely to occur in the section y = 0 (Fig. 1) at $\sigma_c^{ef} = 0.9\,\sigma_c^{coh}$.

Then the distance between cracks C_c will be determined:

$$C_c = \frac{1}{k}\ln\left(0,1 + \frac{h_c\cdot\left(\sigma_c^t + \sigma_c^r\right)}{\varepsilon_{kp}}\cdot\left(\frac{1}{E_c h_c} + \frac{1}{E_b H_b}\right)\right) \tag{6}$$

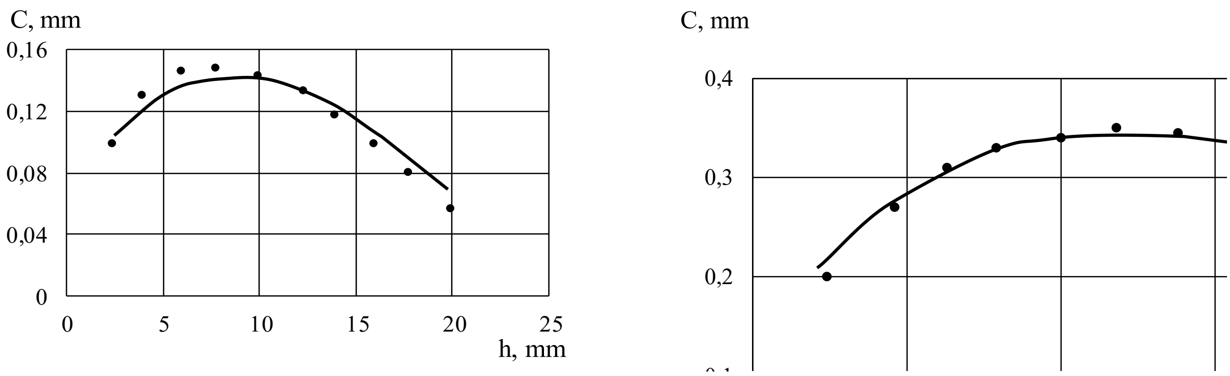
The values of residual stresses σ_c^r during the coating application varied in the range of 350…500 MPa. Temperature stresses σ_c^m varied in the range of 140…180 MPa. The dependences of the discrete section size on the coating thickness for different values of $\varepsilon_{кр}$, σ_c^r and σ_c^m are shown in Fig. 2 and Fig. 3.



a b

Fig. 2. Dependence of the size of the discrete section C_c on the coating thickness h_c for ε_{crit} =0,11…0,20%; a) σ_c^r = 500 MPa; σ_c^m = 160 MPa; b) σ_c^r = 400 MPa; σ_c^m = 160 MPa.

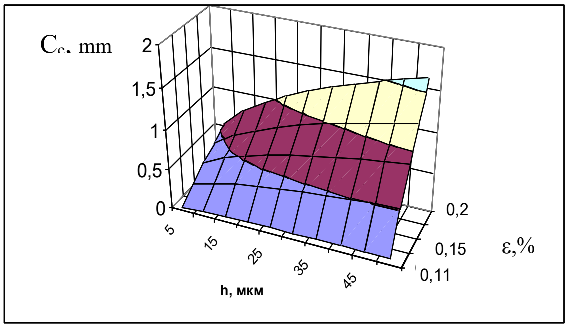
The surfaces of the dependence of the size of the discrete section C_c on the coating thickness h_c and the critical deformation of the base ε_{crit} are shown in Fig. 4.



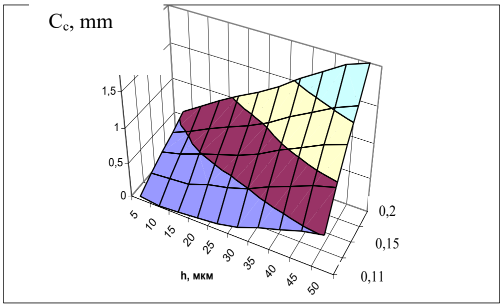
b)

a)

Fig. 3 Dependence of the size of the discrete section C_n on the coating thickness h_c at σ_c^r = 350 MPa; σ_n^m = 180 MPa: a) ε_{crit} = 0.11% b) ε_{crit} = 0.13%



a



b

Fig.4 Dependence of the size of the discrete section of the section C_c on the coating thickness h_c and the critical deformation of the base ε_{crit}: a) σ_c^r =500 МПа; b) σ_c^r = 400 МПа

An experimental test of the optimal size of the discrete section C_c of the discrete coating was carried out under sliding friction. The dependence of the weight wear on the continuity of the discrete coating ψ is shown in Fig. 5. A steel sample served as a counterbody.

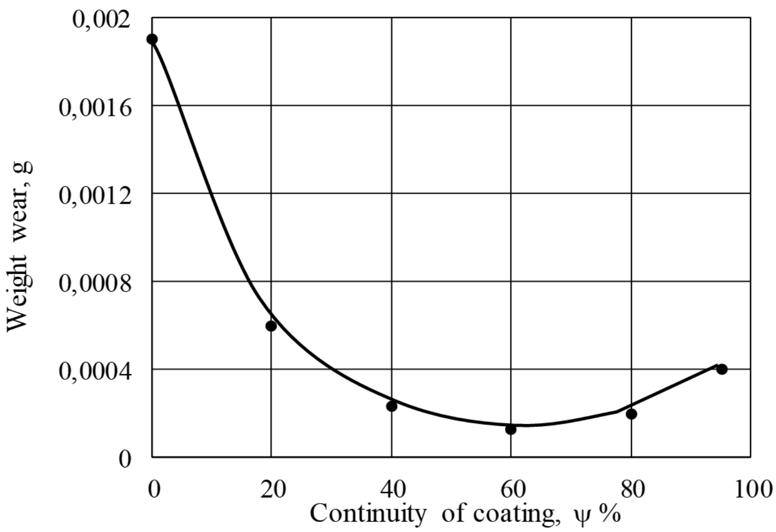
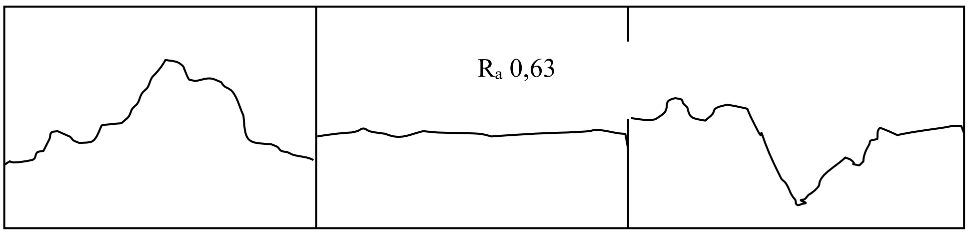


Fig. 5. Dependence of weight wear on the continuity of the coating ψ

Minimum wear occurs at ψ = 60%, which corresponds to the coating area in the form of discrete circular sections with a diameter size equal to C_c.

A change in the continuity ψ of the discrete coating changes the wear mechanism. At ψ<40%, the adhesive wear mechanism is observed. In the range ψ = 50…70%, the most preferable type of wear occurs - abrasive. At ψ>70%, wear by peeling and chipping of coating particles is observed. This is confirmed by studying the profilograms of the friction surfaces (Fig. 6).



а) б) в)

Fig. 6. Friction surface profile of a discrete coating: а) ψ<40%; б) ψ=50…70%; в) ψ>70%

Conclusions

The technological processes of ESA are based on the concept of obtaining continuous layers, which is achieved by multiple passes of the electrode along the surface being hardened. This leads to a decrease in the productivity of the hardening process, to a decrease in a number of physical and mechanical properties of the alloyed layer, and in some cases even leads to its destruction.

The principle of discrete structure coatings made it possible to organically combine the physical processes underlying pulsed hardening methods with a discrete structure that determines their service properties.

References

1. Bondarenko L.I., Puzrin L.G. Argono-dugovaya poverhnostnaya zakalka kak sredstvo uprochneniya artillerijskih stvolov. Artillerijskoe i strelkovoe vooruzhenie: Sb. st., vyp.2 Kiev, GNTC ASV, 2000. S.105-107.
2. Schlett V., Stuke H., Weiss H. Morphology and erosive wear of Fe-Cr-coatings for gun bores deposited by phisical vapor deposition. Vac. Sci and Tehnol. 986, A4, №6. P. 3032-3037.
3. Novikov N.V., Bidnyj A.A., Lyashenko B.A. i dr. Metody uprochneniya poverhnostej mashinostroitelnyh detalej. Kiev, ISM AN USSR. 1989. 112 s.
4. Aleksandrovskij A.N., Yakovenko P.M. Vliyanie galvanicheskih hromovyh i hromnikelevyh pokrytij na prochnost obrazcov iz stali 38HN3MFA. Artillerijskoe i strelkovoe vooruzhenie: Sb. st. Kiev, GNTC ASV, 1999. S.145-147.
5. Komnackij A.L., Gladkij E.D., Roik T.A. Nekotorye mehanicheskie osobennosti processa hromirovaniya poverhnosti kanala stvola kalibra 30 mm. Artillerijskoe i strelkovoe vooruzhenie: Sb. st. Vyp.6. Kiev, GNTC ASV, 2002 S. 31-34.
6. Aleksandrovskij A.N., Melnik V.P., Dudnik M.I. Sluzhebnye svojstva legirovannyh elektroliticheskih hromovyh pokrytij. Artillerijskoe i strelkovoe vooruzhenie: Sb. st. Kiev: GNTC ASV, 1999. S. 153-156.
7. Lapshin S.P., Provolockij A.E., Dudnik M.I. i dr. Issledovanie elektroerozionnogo uprochneniya vnutrennih poverhnostej trub specialnogo naznacheniya. Sb. trudov 1-j Mezhdunar. konf. «Artillerijskie stvolnye sistemy, boepripasy, sredstva art. razvedki i upravleniya ognem». Kiev, GNTC ASV. 1997. S. 260-271.
8. Provolockij A.E., Lapshin S.P., Melnik V.P. Ob elektroiskrovom uprochnenii Stvolov. Artillerijskoe i strelkovoe vooruzhenie: Sb. st. Kiev, GNTC ASV. 1999. S. 172-175.
9. Lyashenko B.A., Kuzema Yu.A., Digam M.S. Uprochnenie poverhnosti metallov pokrytiyami diskretnoj struktury s povyshennoj adgezionnoj i kogezionnoj stojkostyu. Kiev, IPP AN USSR. 1984. 57 s.
10. Lyashenko B.A., Movshovich A.Ya., Dolmatov A.I. Uprochnyayushie pokrytiyah diskretnoj struktury. Tehnologicheskie sistemy. 2001. № 4 (10). S. 17-25.
11. Lyashenko B.A., Cygulev O.V., Kuznecov P.B. Neobhodimo li vsegda povyshat adgezionnuyu prochnost zashitnyh pokrytij. Problemy prochnosti. 1987. № 5. S. 70-74.
12. Umanskij E.S., Lyashenko B.A. Usloviya adgezionnoj i kogezionnoj ravnoprochnosti zharostojkih pokrytij, Kosmicheskih issledovanic na Ukraine. 1975. Vyp.6. S. 58-64.
13. Lyashenko B.A., Aleksyuk M.M., Kuzovkov E.G. Povyshenie dolgovechnosti detalej mashin putem racionalnogo konstruirovaniya zashitnyh pokrytij. Sb. trudov 1-j Mezhdunar. konf. «Artillerijskie stvolnye sistemy, boepripasy, sredstva art. razvedki i upravleniya ognem». Kiev, GNTC ASV, 1997. S. 118-132.
14. Lyashenko B.A., Rutkovskij A.V., Soroka E.B., Lipinskaya N.V. O snizhenii ostatochnyh napryazhenij v vakuum-plazmennyh pokrytiyah. Probl. prochnosti. 2001. №4. S.62-67.

Анттонюк В.С., Лопата Л.А. Оптимізація дискретної структури електроіскрових покриттів

У наведеній статті розглянуто недоліки хромових покриттів та показано можливість їх усунення шляхом отримання покриттів дискретної структури. Принцип покриттів дискретної структури дозволяє органічно поєднати фізичні процеси, що лежать в основі імпульсних методів зміцнення, з дискретною структурою, що визначає їх службові властивості. Показано та обґрунтовано, що метод електроіскрового легування є найбільш підходящим для нанесення дискретних покриттів, бо цей процес є дискретним за своєю природою. Перевага дискретних покриттів полягає у відсутності розміцнювального ефекту при переході крихкої тріщини з покриття в основний метал за рахунок надмірно високої міцності адгезійної. Висока когезійна та адгезійна стійкість окремих дискретних ділянок покриття досягається шляхом обмеження нормальних напруг у покритті та дотичних у площині адгезійного контакту з основою за рахунок зміни розмірів та форми окремої ділянки. Ця стаття присвячена визначенню оптимальних параметрів дискретної структури. Необхідна конструкція покриття визначається розрахунковим методом на основі моделі, що описує напружено деформований стан покриття.

Ключові слова: хромирование, электроискровое легирование, дискретное покрытие, напряженно-деформированное состояние, когезионная и адгезионная прочность, термомеханическая стойкость, сплошность покрытия, износ