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MODELING AND OPTIMIZATION OF WEAR-RESISTANT COATINGS PRODUCTION USING ECD TECHNOLOGY

The paper considers the modeling and optimization of the formation of protective layers based on titanium using ESD technology. As an optimization parameter, the wear resistance index for the ESD-Ti-AlT system was chosen. The mathematical dependences of the microhardness on the thickness of the obtained titanium coatings on the composition of the composite powder charge (CPS), which are described by a fifth-order polynomial, were established. The geometric interpretation in triangles consisting of basic elements at saturation with titanium was obtained and the following dependences were established: microhardness of titanium diffusion layers — on the composition of CPS.

Ключові слова*: mathematical modeling, wear resistance, ESD technology, temperature, optimization, microhardness.*

У роботі розглянуто моделювання та оптимізація формування захисних шарів на базі титану з використанням технології ECD. В якості параметру оптимізації обрано показник зносостійкості при титануванні для системи ECD-Ti-AlT. Встановлено математичні залежності мікротвердості по товщині отриманих титанових покриттів від складу скомпозиційного порошкового середовища (КПС), які описуються поліномом п'ятого порядку. Отримано геометричну інтерпретацію в трикутниках, що складаються з основних елементів при насичені титаном та встановлено залежності: мікротвердість титанових дифузійних шарів — від складу КПС.

Keywords*: математичне моделювання, зносостійкість, технологія ECD, температура, оптимізація, мікротвердість.*

Problem's Formulation

In mechanical engineering, the durability of parts of machines and mechanisms operating under conditions of friction and wear is one of the main factors of their durability, which is surface hardness.

Currently, there is a need to improve the physical, mechanical and operational properties of materials. With an increase in the content of alloying elements, physical and mechanical characteristics: strength, hardness, wear resistance increase, but the probability of brittle fracture increases, and the cost of the alloyed metal also increases. Currently, this explains the growing interest in coatings. The need to apply the coating is primarily due to the necessary operational properties. The priority direction of the development of surface strengthening at the modern level is the development, creation and implementation of new technologies of chemical and thermal treatment (CTT). After it is carried out on operational surfaces, diffusion layers of high quality are obtained, which then turn into the main material, which is positive from the point of view of strength and stability. The idea of creating a diffusion zone with a specific chemical composition on their surface attracts the attention of specialists, primarily due to its rationality. Mathematical modeling of the production of diffusion coatings solves the coupled nonlinear two-dimensional problem of the ECD theory (ECD — the energy component of the diffusion process), which includes the heat transfer equation, reaction kinetics in the ECD wave, and the problem of the theory of diffusion in a non-stationary thermal field. Calculating the temperature fields at saturation in the CSM allows you to establish two zones: the heating zone and the thermal self-ignition zone. The planes of the temperature field increase depending on the auto-ignition temperature and the maximum temperature of the process.

On the basis of technical achievements in the fields of mechanics, metallurgy and informatics, new saturating environments are being created, which allow to minimize energy costs and increase the speed of formation of protective coatings with predetermined properties based on mathematical modeling of the process of saturation of the surface of steels and optimization of CSM, which are considered in the scientific literature [1—3].

Analysis of recent research and publications

The authors of [4] proposed a CTT scheme, which does not involve sealing the container, evacuating it or filling it with argon, as well as exciting mechanical vibrations of the container and the product. In addition, a saturating medium is used, which undergoes an exothermic reaction when heated and ignited. Coal powder was chosen as such a medium, which plays the role of a source of atomic carbon, a micro-arc-forming medium and has a significant thermal effect during combustion. In addition, to localize the process of saturation of a given area of the surface of the product, the processing scheme provides for a minimum ratio of the areas of the electrodes and the product (10:1), this allows to increase the current density on the area of the processing surface to be saturated by an order of magnitude. To obtain a uniform depth of the cemented layer, you need to have a strengthening surface equidistant from the walls of the container, otherwise the areas of the surface located closer to the walls of the container are heated earlier and to a higher temperature and have a greater depth of the cemented layer. The microarc CTT method has a number of significant advantages compared to analogues and allows you to form a diffusion layer with a depth comparable to traditional CTT methods within a few minutes. The implementation of this method does not require complex equipment, which allows creating diffusion layers on large-sized products and localizing strengthening in depth and geometry within specified limits by changing the shape and size of the counter electrode. The consumption of powder material in this technology can be reduced to a minimum, since, as was shown, the main saturation process takes place in a small volume of powder directly adjacent to the strengthening surface.

The existing CTT methods [7] can be divided into four main groups: saturation in solid, liquid, gaseous media and in plasma. The peculiarities of each method are determined by the aggregate state of the saturating medium and the properties of the component substances. In CTT, heating methods of different nature and speed are used: traditional (slow) furnace heating, intensive (fast) electric heating (induction, electric contact, etc.), heating with concentrated energy flows (for example, a laser beam). The selection of the heating mode is carried out taking into account the thermal properties of the saturating material, the configuration of the products and other factors. The entire technological cycle of CTT in solid and liquid media, in coatings can be carried out in oxidizing and controlled atmospheres or in a vacuum. In thermal and CTT, controlled atmospheres are used, which are divided into neutral, protective and special (saturating) atmospheres.

Only traditional saturation processes: nitriding, cementation, nitrocementation, and cyanation have received wide industrial application. Galvanizing alitizing, boriding, chroming, silicification is used to a much lesser extent. The most effective anti-corrosion, erosion-resistant, heat-resistant and other multi-component diffusion layers have not yet found wide industrial application [9]. At the same time, the future belongs to new and, as a rule, multicomponent diffusion layers. On the one hand, this is due to the growing shortage of special steels and alloys; in the other — traditional CTT processes that do not meet the requirements for properties that industry sets for products working in particularly extreme operating conditions.

Formulation of the purpose of the research

The purpose of the work is the search for effective powder CSMs, which allows the formation of intermetallic protective layers on structural materials with different carbon content using ECD technological processes. As an optimizing factor, the surface hardness is adopted, which has a direct proportional effect on the wear resistance in the conditions of friction-sliding and shock-dynamic loading of parts working in aggressive conditions of metallurgical production. Solving this problem allows to ensure the durability of equipment in mechanical engineering and metallurgy.

Presenting main material

The wear characteristic ДI is the change in mass of the sample made of steel 45, on which the coating was obtained at t_m= 1000 °C і ф_h= 150 min. The choice of the rational composition of the charge for carrying out the saturation process under conditions of thermal self-ignition is carried out on the basis of the results of studies of the thermal kinetics of the ECD process, microhardness, residual stresses and microfragility [10—12].

Optimization parameters: I1 is the index of wear resistance during titanation for the ECD-Ti-AlT system. The choice of the main level and intervals of variation is based on the fact that the introduction of ESD, when: titanation is less than 5—9 % by mass. leads to the disruption of the wave of combustion of thermal self-ignition. Based on the study of changes in characteristic temperatures in oxide-free composite saturating media, the necessary amount of ECD for the coating formation process is determined. Al_2O_3 is used as a ballast admixture to obtain a one hundred percent composition of powder CSM-charges No. 1. The process of formation of protective coatings in the mode of thermal self-ignition can be conditionally divided into five stages — inert heating of the ECD mixture to the temperature of self-ignition, thermal self-ignition, heating of parts, isothermal exposure and cooling.

At the initial stage (stage 1), inert heating of the mixture occurs. When a diffusing element, titanium or chromium, is used as a supplier, the formation of a titanium or chromium layer is observed.

At stage 2 — the stage of thermal self-ignition, the self-ignition temperature rises at a rate of 200—400 °C/s to a maximum value. At this stage, along with the formation of active titanium or chromium atoms, reactions occur for the formation of elemental chromium and their combination with carriers (fluorine, chlorine and iodine), with the formation of volatile halides. If the activation energy of the interaction of the elements of the charge with the carrier is less than the activation energy of the main reduction process, then the formation of volatile halides will proceed quasi-stationary as the main reaction proceeds. If the self-ignition temperature is lower than the temperature at which the volatile halide begins to form intensively, then for this case, the formation of halides occurs only at the stage of unsteady temperature growth. When the maximum temperature is reached, which converts the pyrolysis temperature of chromium diiodide, its rapid decay occurs.

At stage 3 — the stage of heating products, the temperature drops to the process temperature Tp due to the reception of the released heat by the products. Active atoms begin to diffuse into the substrate and the carbide phases are alloyed with titanium or chromium. Doped titanium or chromium phases begin to form.

At stage 4 — the stage of isothermal exposure, a constant diffusion flow of formed active atoms of chromium, aluminum and titanium is formed. The diffusion layer increases and the chromium aluminized layers are doped with titanium. With an increase in isothermal exposure, an increase in the layer thickness occurs. The growth of the layer obeys a parabolic law.

At the 5th stage — the stage of cooling, a diffusion layer is formed with a lower intensity due to a decrease in the diffusion coefficient of titanium and chromium due to a drop in temperature. The layer consists of two phases: the outer one, which is titanides and chomoalitides, and the inner, carbide phase.

Estimated levels of variation intervals (Tabl. 1), characterize their changes and coding schemes in a wide range of studied values.

Table 1. Factors for the ECD–Ti–AlT system

Characteristic	Factors		
	ECD %, wt.	Ti %, wt.	GTA %, wt.
Code	X_1	X_2	X_3
Basic level	20	15	5
Variation interval	4	3	2
Lower level	16	12	3
Upper level	24	18	8

The numerical value of the regression coefficients and their significance, determined taking into account the variance difference for each response function, as well as the significance test by the Student's test and the assessment of the adequacy of the model by the Fisher test.

As a result of the regression analysis, equations are obtained that show the dependence of the wear resistance of protective coatings on the mode of thermal self-ignition and the content of alloying elements: in coded form

$$I_1 = 75{,}933 + 1{,}7X_1 + 0{,}6X_2 - 1{,}9X_3 - 2{,}1667X_1^2 - 2{,}6667X_2^2 + 6{,}8333X_3^2 - 0{,}5X_1X_2 + \quad (1)$$

$$+ 1{,}5X_1X_3 - 0{,}5X_1X_2 - 3X_2X_3.$$

Model adequacy testing shows that they can be used to predict response functions at any factor values between the upper and lower levels. For this, it is advisable to switch to natural variables using the translation formula presented in the following form

$$X_{ij}^{k} = \frac{X_{ij}^{n} - X_{ij}^{o}}{\Delta_{i}}, \tag{2}$$

where X_{ij}^{k} — coded value of the ith factor of the subject in the j equation; X_{ij}^{n} — the natural value of the i-th factor studied in the j equation; X_{ij}^{o} — value of the i-th factor of the subject in the j equation at the basic level; Δ_{i} — value of the investigated variation interval of the i-th factor.

Coefficients whose absolute value is equal to the confidence interval Дb or more should be considered statistically significant. Statistically insignificant coefficients can be excluded from the models. By replacing the variables X_i in equations (1) with the right-hand side of equation (2) and the subsequent reduction of similar ones, we obtain natural equations characterizing the effects of the mode of thermal self-ignition and the content of saturating elements on the wear resistance of protective coatings:

$$ДI_4 = -43{,}44 + 5{,}84ECD + 11{,}39Ti - 10{,}53GTA - 0{,}14ECD^2 - 0{,}3Ti^2 + 1{,}71GTA^2 - 0{,}57\ TiGTA. \tag{2}$$

To assess the adequacy of the equation, a calculation is made based on the obtained regression equations for the rational mode of thermal autoignition. Calculation results are compared with experimental data. It was established that the error between the calculated and experimental values of the response function does not exceed 2.5 %.

The response surface (Fig. 1) of the obtained mathematical model is represented by a three-dimensional graphical dependence.

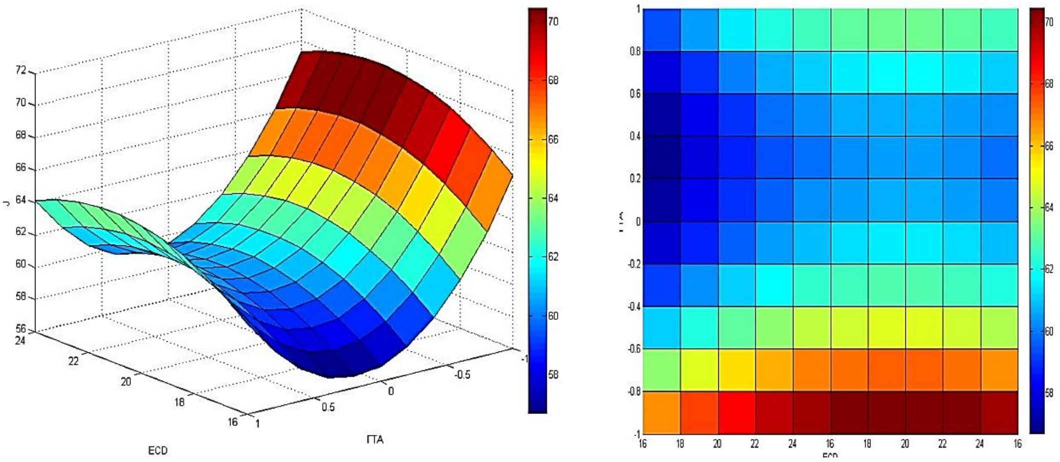


Fig. 1. Effect of ECD and GTA content (% wt.) in CSM-charges №1 on wear resistance (I_1)

A rational composition of the CSM charge is recommended: 16% ECD + 18% Ti + 61% Al_2O_3 + 2% NH_4I + 3% AlF_3, to obtain wear-resistant protective coatings on steel 45.

The distribution of microhardness over the thickness of the titanium diffusion layers upon saturation in CSM №1 (Fig. 2) is: on ductile iron: H_{100} = 8000 MPa, on steel 20: H_{100} = 9000 MPa (has the following phases: Fe_2Al_5 with TiAl, Cr_2Ti inclusions. Next there are phases: FeAl, and a solid solution of titanium, aluminum and chromium in б-iron.

It was established and experimentally confirmed that the microhardness depends on the thickness of the obtained titanium coatings on the composition of the composite saturating medium, which is described by a fifth-order polynomial. So when saturated in CSM:

$$y = -1E\text{-}05x^5 + 0{,}0025x^4 - 0{,}132x^3 - 2{,}1731x^2 + 48{,}852x + 16437 \quad (У8) \tag{3}$$

$$y = 4E\text{-}06x^5 - 0{,}0012x^4 + 0{,}1129x^3 - 4{,}7712x^2 + 16{,}688x + 8266{,}6 \text{ (technical Fe)} \quad (4)$$

$$y = 4E\text{-}06x^5 - 0{,}0007x^4 + 0{,}0501x^3 - 3{,}3135x^2 + 12{,}507x + 15492 \text{ (steel 45)} \quad (5)$$

$$y = -2E\text{-}06x^5 + 0{,}0001x^4 + 0{,}0493x^3 - 4{,}7052x^2 + 3{,}6857x + 8972{,}9 \text{ (steel 20)} \quad (6)$$

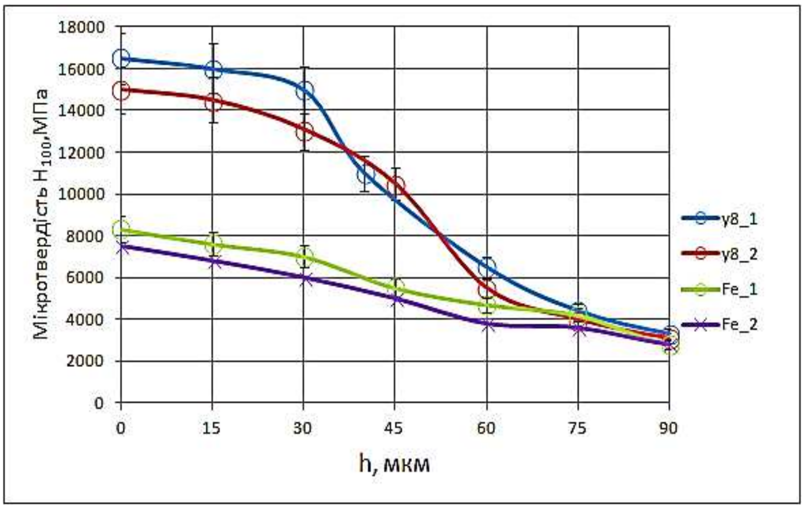
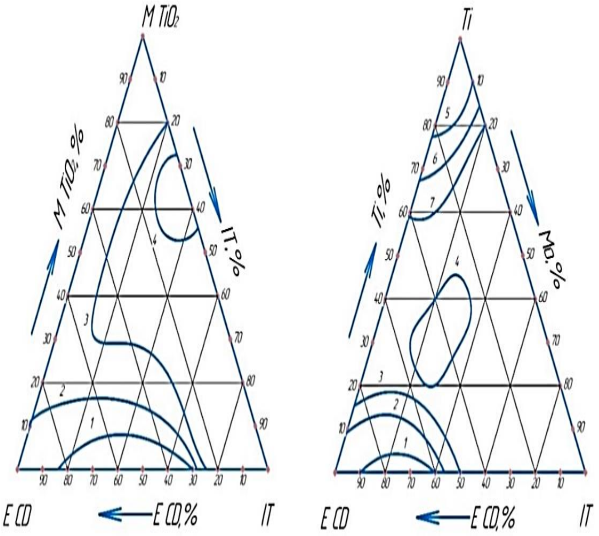


Fig. 2. Distribution of microhardness by thickness of titanium diffusion layers: U8 steel and technical iron: 1— CSM №1; 2 — CSM № 2

The geometric interpretation in the triangle consisting of the main elements during titanium saturation establishes the dependence of the microhardness of the vanadium diffusion layers on steel 45 on the composition of the composite saturating medium. Thus, in system №1 (Fig. 3), it allows to distinguish three areas of the composition of saturating mixtures, in which the microhardness values are: 13000—114500 MPa, 15000 MPa i 15000—16500 MPa, which are determined by the following ratios of the main saturating components; in the first region, (% wt.): 5—16 titanium, 50—90 ECD, in the second: 25—55 ECD, 20—46 titanium and in the third: 10—40 ECD, 60—90 titanium.



CSM №1 (1–13000, 2–14000, 3–14500, 4–15000, 5–16500, 6–16000, 7–15000)

Fig. 3. Microhardness (MPa) of titanium diffusion layers on steel 45 depending on the composition of the composite saturating medium

Conclusions

Modeling was carried out to find optimal mixtures of EDP powders to produce intermetallic wear-resistant protective coatings on technical iron and steels 20, 45, and U8A using EDP technology of high-temperature synthesis. The structures of protective layers and their wear resistance under sliding friction conditions were investigated. The best wear resistance among the considered coatings have titanium coatings on steels 45, and U8A. It was established and experimentally confirmed that the microhardness depends on the thickness of the obtained titanium coatings on the composition of the composite saturating medium, which is described by a fifth-order polynomial.

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МОДЕЛЮВАННЯ ТА ОПТИМІЗАЦІЯ ОТРИМАННЯ ЗНОСОСТІЙКИХ ПОКРИТТІВ З ВИКОРИСТАННЯМ ТЕХНОЛОГІЇ ECD

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Реферат

У машинобудуванні довговічність деталей машин і механізмів, що працюють в умовах тертя та зносу одним з головних факторів їх довговічності є твердість поверхні.

На даний час виникає необхідність підвищення фізико-механічних і експлуатаційних властивостей матеріалів. Зі збільшенням вмісту легуючих елементів фізико-механічні характеристики: міцність, твердість, зносостійкість зростають, але ймовірність крихкого руйнування

підвищується, також збільшується і вартість легованого металу. В даний час, це пояснює все зростаючий інтерес до покриттів. Необхідність застосування покриття, перш за все обумовлена необхідними експлуатаційними властивостями. Пріоритетним напрямом розвитку зміцнення поверхні на сучасному рівні є розробка, створення та впровадження нових технологій хіміко-термічной обробки (ХТО). Після її проведення на експлуатаційних поверхнях отримують дифузійні шари високої якості, які далі переходять в основний матеріал, що є позитивним з точки зору міцності та стійкості. Ідея створення на їх поверхні дифузійної зони із специфічним хімічним складом привертає увагу фахівців, передусім, завдяки своїй раціональності. Математичне моделювання отримання дифузійних покриттів вирішує сполучену нелінійну двомірну задачу теорії ECD (ECD — енергетична складова дифузійного процесу), яке включає рівняння тепло переносу, кінетики реакції у хвилі ECD та задачу теорії дифузії в нестаціонарному тепловому полі. Розраховуючи температурні поля при насиченні в КНС дозволяє встановити дві зони: зони прогрівання та зону теплового самозаймання. Площини температурного поля збільшуються в залежності від температури самозаймання та максимальної температури процесу.

Характеристикою зносу ДІ служить зміна маси зразка, виготовленого зі сталі 45, на якому отримано покриття при $t_п$ = 1000 °С і $ф_в$ = 150 хв. Вибір раціонального складу шихти для проведення процесу насичення в умовах теплового самозаймання проводиться на підставі результатів досліджень теплової кінетики ECD-процесу, мікротвердості, залишкових напружень та мікрокрихкості.

У результаті регресійного аналізу отримуються рівняння, що показують залежність зносостійкості захисних покриттів від режиму теплового самозаймання та вмісту легуючих елементів: в кодованому виді $I_1 = 75{,}933 + 1{,}7X_1 + 0{,}6X_2 - 1{,}9X_3 - 2{,}1667X_1^2 - 2{,}6667X_2^2 + 6{,}8333X_3^2 - 0{,}5X_1X_2 + 1{,}5X_1X_3 - 0{,}5X_1X_2 - 3X_2X_3$. В натуральному виді: $ДI_4 = -43{,}44 + 5{,}84ECD + 11{,}39Ti - 10{,}53ГТА - 0{,}14ECD^2 - 0{,}3Ti^2 + 1{,}71ГТА^2 - 0{,}57\ TiГТА$.

Рекомендовано раціональний склад КНС-шихти: 16% ECD + 18% Ti + 61% Al_2O_3 + 2% NH_4I + 3% AlF_3, для отримання зносостійких захисних покриттів на сталі 45.

Геометрична інтерпретація в трикутнику, що складається з основних елементів при насиченні титаном, встановлює залежність мікротвердості ванадієвих дифузійних шарів на сталі 45 від складу композиційного насичуючого середовища. В системі № 1 вона дозволяє виділити три області складу насичуючих сумішей, в яких значення мікротвердості становлять: 13000—114500 МПа, 15000 МПа і 15000—16500 МПа, які задаються наступними співвідношеннями основних насичуючих компонентів; в першій області, (% мас.): 5—16 титану, 50—90 ECD, у другій: 25—55 ECD, 20—46 титану і у третій: 10—40 ECD, 60—90 титану.

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