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STATEMENT OF THE PROBLEM OF CONTROLLING DIFFUSION SATURATION OF POROUS COATINGS UNDER ION NITRIDING CONDITIONS

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Abstract. *This study examines the problem of improving the functional properties of porous coatings obtained by thermal spraying during the restoration of ship machinery parts. The implementation of "anomalous mass transfer" in the process of pulsed ion nitriding and the need to control this phenomenon through controlled parameters, which in turn form a coating with a given set of properties, are shown. To solve this problem, such thermodynamic approaches as diffusion theory of elasticity and locally unbalanced thermodynamics were used. An analysis of modern models of mechanics describing interrelated processes of force, thermal and diffusion nature and physical concepts of the influence of structural parameters on the intensity of mass transfer in porous media are presented. Based on the analysis, a statement of the problem of controlling the diffuse saturation of porous coatings under conditions of thermal cyclic ion nitriding is proposed.*

Key words: *thermal spray coatings, ion nitriding, diffusion process, ship mechanisms, porosity of coatings, operation characteristics, diffusion rate*

Introduction.

One of the tasks of modern engineering of surface is to ensure the strength and durability of surface layers, and in the event of loss of geometric characteristics of parts due to wear, to restore their profile while simultaneously providing new areas of the surface with the necessary set of performance properties. A characteristic feature of surface hardening methods is the impossibility of increasing the performance properties of a part for the entire range of operating modes. The elimination of this disadvantage of coatings is achieved by using multi-operation technologies and applying multilayer, multifunctional coatings [1]. One of the technologies used in modern shipbuilding is gas-thermal spraying (GTS) of coatings [2]. Its use is due to the sufficient simplicity of restoring the geometry of the surfaces of parts, the relatively low cost of equipment and the total cost of restoring the worn surface [2]. At the same time, coatings obtained using GTS have a number of disadvantages. These include low adhesion strength to the base, high porosity and insufficient hardness [2]. These properties can be significantly improved by additional chemical-thermal treatment, in particular by thermal-cyclic ion-plasma nitriding (TC IA). The use of this version of integrated technologies allows for a significant increase in the durability of ship mechanism elements operating in aggressive conditions [2].

The aim of the work.

The aim of the work is to construct mathematical relationships that allow for the control of diffuse saturation of porous coatings under ion nitriding conditions to improve the performance characteristics of surface layers.

Main text.

The effect of accelerated diffusion of a substance, called "anomalous mass transfer", is realized in various types of mechanical and thermal processing of materials and is currently used to improve the performance properties of surface layers of parts operating under contact loads. The process of anomalous mass transfer is especially clearly realized in the TC IA [2]. The widespread introduction of this effect leads to the need to control this phenomenon - the choice of such parameters of external influences that form a coating with a given set of properties. To solve this problem, we will use the approaches of thermodynamics - the diffusion theory of elasticity of Podstrigach Ya.S. and locally nonequilibrium thermodynamics of Burak Ya.Y. [3, 4]. The factors influencing the rate of mass transfer include: temperature, parameters of external force effects, structural and phase state of the material at the initial moment of time. In this case, the strain rate is one of the determining factors, and the dependence of the diffusion coefficient in the medium on the strain rate is:

$$D_M = D_0 + C\left|\dot{\varepsilon}\right|^{\alpha} \times \exp\left(\frac{\beta}{T}\right), \quad (1)$$

In this formula:

D_0 - diffusion coefficient in the absence of deformations, $\dot{\varepsilon}$ - rate of deformations, α, β - constants, T - temperature.

The ion nitriding process includes the following stages [9, 10]:

1. Supply of nitrogen from the appropriate medium to the surface of the part.

2. Formation of a boundary layer at the surface of the part, where dissociation of the nitrogen-containing medium and adsorption of nitrogen atoms by the surface occur at the "medium-metal" interphase boundary.

3. Penetration of nitrogen atoms through the surface into the material of the part.

4. Diffusion of nitrogen atoms into the surface layer along grain boundaries and through grains.

In this case, the control parameters are:

- saturation temperature;
- gas pressure;
- gas composition;
- full processing time;
- the form and temporal intensity of energy input.

If the first four parameters are quite important from the point of view of obtaining coatings with a given level of properties, then the last characteristic determines the possibility of accelerating diffusion processes and, as a result, the formation of surface layers of parts with increased operational characteristics.

To take into account the forms and temporal features of external energy input within the framework of the empirical relations described above, consider a vector quantity - the flow of energy input, described by the relation:

$$\vec{J}_E(s,t) = -\left(\frac{\partial^2 E}{\partial \nu \partial \tau}\right)\vec{n}(s), \qquad (2)$$

In this formula:

$\vec{J}_E(s,t)$ - vector of the energy input flux at a point on the surface, s;

$\vec{n}(s)$ - external unit normal to the surface at the point;

$\left(\frac{\partial^2 E}{\partial \nu \partial \tau}\right)$ - mixed derivative of the energy input with respect to time and with respect to the normal to the surface.

When constructing relation (2), a priori assumptions were used that the boundary of the body is a smooth surface, at each point of which it is possible to construct a unit normal and find the derivative along the surface in any considered time interval.

Let's represent $\vec{J}_E(s,\tau)$ in the form:

$$\vec{J}_E(s,\tau) = -\left|J_E^1(s)\right| \times \left|J_E^2(\tau)\right| \vec{n}(s), \quad (3)$$

In this formula:

$\vec{J}_E(s,\tau)$ - component of the flow responsible for the shape of the energy input;

$J_E^2(\tau)$ - component of the flow responsible for the temporary passage of the energy input.

In accordance with the works on locally unbalanced thermodynamics [5, 6], we write:

$$J_E^2(\tau) = -J_E^2(\tau=\tau_0) + \left.\frac{\partial J_E^2(\tau)}{\partial \tau}\right|_{\tau=\tau_0} \tau + \frac{1}{2}\left.\frac{\partial^2 J_E^2(\tau)}{\partial \tau^2}\right|_{\tau=\tau_0} \tau^2 = \Pi_1 + \Pi_{2\tau} + \Pi_{3\tau^2}, \quad (4)$$

In this formula:

$\Pi_1 = J_E^2(\tau=\tau_0)$ - value of the time component of the energy flow at the initial moment of time;

$\Pi_2 = \left.\frac{\partial J_E^2(\tau)}{\partial \tau}\right|_{\tau=\tau_0}$ - value of the high-speed time component of the energy flow at the initial moment of time;

$\Pi_3 = \frac{1}{2}\left.\frac{\partial^2 J_E^2(\tau)}{\partial \tau^2}\right|_{\tau=\tau_0}$ - amount of acceleration of the time component of the energy flow at the initial moment of time.

The representation of the value $J_E^1(s)$ depends on the a priori assumptions of the geometric parameters of the energy input region.

When diffusion processes occur in cellular media, the diffusion coefficient depends significantly on the structure of the medium [11, 12], which in the general case can be specified by an arbitrary number of variables.

In this regard, taking into account the relationship (1) - (4), we will present the diffusion coefficient of porous coatings, which depends both on the parameters of external energy effects and on the porosity characteristics of the sprayed coating:

$$D_0 = D_M\left(\left\{\Pi_k^i\right\}_{j=1,...;k=1...};\left\{\theta_j\right\}_{j=1}\right), \tag{5}$$

In this formula:

D_M - mass transfer coefficient;

Π_k^i - parameters of energy impacts during technological modification;

θ_j - variables describing the porosity of the coating structure;

i,j,k - running indices.

The choice of parameters Π_k^i depends on the level of specification of the task of describing energy effects (taking into account force, thermal and other types of loads), the assignment of variables θ_j is carried out taking into account the required level of detail of the porous structure of the surface. Under the assumption of isotropy of the porous structure, the quantities θ_j are taken as variables of a scalar nature.

Since in the general case the establishment of dependencies of type (5) is currently an open problem, we propose the following representation of the mass transfer coefficient in the form of a linear additive expansion in a series in terms of the main variables:

$$D_M = \sum_{i,k} C_{i,k}\Pi_k^i + \sum_j A_j\theta_j, \tag{6}$$

In this formula:

$C_{i,k}$, A_j - empirical coefficients.

Note that the assignment of the mass transfer coefficient in the form (2) is in accordance with modern studies on the physical characteristics of diffusion under conditions of high-intensity energy impacts [11, 12].

When setting the problem of controlling the diffusion saturation of surface layers, it is important to select the criterion (functional) according to which the optimal solution will be established.

In this paper, the value (depth) of the saturated layer obtained as a result of technological modification is proposed as an optimality criterion:

$$L \to \max \quad (7)$$

Taking into account the dependence of the functional (7) on the parameters of the porosity of the structure and external energy effects

$$L = L\left(\left\{\Pi_k^i\right\}_{j=1,...;k=1...};\left\{\theta_j\right\}_{j=1}\right) \quad (8)$$

the problem of controlling the diffusion saturation of surface layers under conditions of thermocyclic ion nitriding has the form:

$$L = \left\{\frac{\Pi_k^i \text{ - ?}}{L\left(\left\{\Pi_k^i\right\}_{j=1,...;k=1...};\left\{\theta_j\right\}_{j=1}\right) \to \max}\right\} \quad (9)$$

The solution of problem (9) can be carried out using the schedule of functional (8) in the system of basis functions 2 using the method of weighted discrepancies - the Galerkin method, or using numerous approximations using the gradient descent method, based on the model representations of work [5], or extended representations [6].

Conclusion.

Improving the functional properties of porous coatings requires solving the scientific problem of managing diffusion processes in the surface layers of parts obtained by thermal spraying.

An analysis of modern models of mechanics describing interrelated processes of force, thermal and diffusion nature and physical concepts of the influence of structural parameters on the intensity of mass transfer in porous media is presented.

Based on the analysis, a formulation of the problem of managing the diffusion saturation of porous coatings under conditions of thermal ion nitriding is proposed.

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