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CALCULATION OF WEAR RESISTANCE AND DURABILITY OF STRUCTURAL ELEMENTS WITH GRADIENT DIFFUSIVE COATINGS AND METASTABLE PHASES IN THE STRUCTURE OF MATERIALS

УДК. 621.891

Method of calculating of the durability and longevity of structural elements with gradient coatings and metastable phases in the structure of materials after ion nitriding and subsequent quenching to yield the residual nitrogen austenite is presented.

Key words: residual austenite, wear, durability, nitriding, glow discharge

Introduction

Research by many authors [1; 2] shows that the presence of metastable residual austenite in the structure of material has a positive impact on improving of the durability of structural elements in abrasive environment. Under the influence of deformation the metastable austenite is converted into other phases, thus the energy of activation is absorbed, which leads to a slowdown of the fracture in wear.

Methods of chemical and thermal processing – nitriding, carburizing, borating and others are widely used in order to improve the wear resistance and durability of structural elements in friction and wear. Thus the diffusive gradient coatings with improved tribological properties are formed on the surface.

Operating experience of structural elements in friction shows that the most effective method of chemical and thermal processing is nitriding in a glow discharge [3; 7]. However, the literature is not driven the methodology of calculating of the durability of diffusive coatings with metastable phases in the structure of the material.

Nitrided layers consist of nitride zone with stable structure and hardness and transitive zone (zone of internal nitriding) with variable hardness and nitrogen concentration in depth, which decreases from the surface to the base by the exponential dependence (1) and depends on technological parameters of the process of nitriding [8] (Fig. 1).

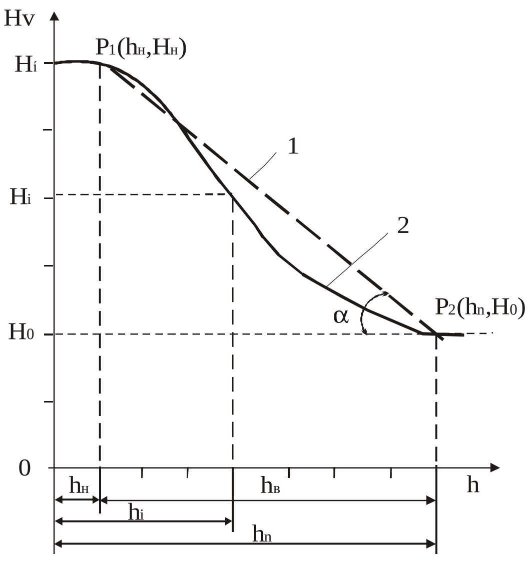

Fig. 1 – Distribution of hardness through the thickness of the nitrided layer:
1 – on linear dependence;
2 – by an exponential dependence

$$H_i = H_0 + \left(H_{\max} \cdot k_4 - H_0\right) \cdot e^{\frac{h_i}{k_1 \cdot k_2 \cdot k_3 \cdot (h_n - h_i)}}, \tag{1}$$

where H_0 – the hardness of the base;

$H_{\max}$ – surface hardness of the nitrided layer in optimally nitriding;

H_i – hardness of *i*-ty layer at a distance h_i from the surface;

h_n – the thickness of the nitrided layer, which is the sum of the thickness of nitride zone $h_н$ and the zone of internal nitriding $h_в$;

k_1, k_2, k_3, k_4 – coefficients that depend on the technological parameters of nitriding process (temperature, pressure, medium composition and time of diffusion saturation).

Mean hardness of zone of internal nitriding can be found by the formula:

$$H_{в.с.} = \frac{\int_{h_н}^{h_в} H_i dh}{h_n - h_н}, \tag{2}$$

where $h_н$ and $h_в$ – thickness of the nitride zone and the zone of internal nitriding, respectively;

H_i – hardness of the nitrided layer at a distance h_i from the surface

In case when a change of hardness by depth zone of internal nitriding to approximate by linear dependence of hardness on thickness $h_в$ (Fig. 1), the average hardness H_c of internal nitriding zone is defined by the formula:

$$H_c = \frac{H_н + H_0}{2}, \tag{3}$$

Given the characteristics of the nitrided layer with nitride zone, a zone of internal nitriding and contain residual austenite, we obtain the generalized multifactor model of abrasive wear for each of the zones of the nitrided layer.

Basic material

The calculation of the intensity of wear materials with metastable phases in their structure and nitrided layers on the surface will be carried out in three stages.

The first stage we make a list of all determining and determined quantities with their dimensions. Quantities that are determined will be: the intensity of wear of nitride zone – $\frac{dU_н}{dL_н} = J_н$ and intensity of wear zone of internal nitriding $\frac{dU_в}{dL_в} = J_в$, where $U_н$ and $L_н$ – wear and the way of friction in nitride zone (μm), $U_в$ and $L_в$ – wear and friction path in the zone of internal nitriding (μm).

Determining quantities or the main factors affecting the abrasive wear are:

$P_{\max}$ – maximum pressure in the material cylinder, MPa;

f – coefficient of friction;

δ – clearance between the screw and the cylinder, μm;

χ – diameter of cutting abrasive particle, μm;

A – percentage of residual austenite in the material,%;

H_a – microhardness of abrasive, MPa;

T_e – temperature of extrusion, °C;

T_q – temperature of quenching, °C;

$H_н$ – microhardness of nitride zone, MPa;

$H_в$ – microhardness of zone of internal nitriding, MPa;

H_0 – microhardness of base, MPa;

H_c – average microhardness of zone of internal nitriding, MPa;

In the second stage of the theory of similarity and dimension (TSD) we make dimensionless complexes from determining and determined quantities. In our case, taking into account the working conditions of the extruder during processing feed grains with the addition of minerals containing abrasive particles, the intensity of wear for each of the zones can be expressed as the product of the following complexes:

$$\frac{dU_н}{dL_н} = J_н = k_{wн} \cdot П_н^{x_1} \cdot П_{см}^{y_1} \cdot П_A^{n_1} \cdot П_{Hн}^{m_1} \cdot П_T^{z_1}, \qquad (4)$$

$$\frac{dU_в}{dL_в} = J_в = k_{wв} \cdot П_в^{x_1} \cdot П_{см}^{y_1} \cdot П_A^{n_1} \cdot П_{Hв}^{m_1} \cdot П_T^{z_1}, \qquad (4, a)$$

where $k_{wв}, k_{wн}, x_1, y_1, n_1, m_1, z_1$ – coefficients which are deterdmined from the experiment with regard to operating conditions.

Complexes:

$$П_н = \frac{P_{\max} \cdot f}{H_н}; \qquad (5)$$

$$П_в = \frac{P_{\max} \cdot f}{H_c}, \qquad (5, a)$$

characterizing the stress state of contact and the dimensionless area of contact bodies.

Complex:

$$П_{см} = \frac{\delta}{\chi}, \qquad (6)$$

which takes into account the influence of the size of clearance and the size of the abrasive.

Dimensionless complex:

$$П_A = a \cdot A^2 + b \cdot A + c = K_A, \qquad (7)$$

where a, b, c – coefficients for each material from experiment on wear;

K_A – coefficient taking into account the influence of content of austenite A in the structure of the material on wear (parabolic dependence).

Complex:

$$П_H = \frac{H_a}{H_M} = K_H, \qquad (8)$$

K_H – coefficient which takes into account the effect of the hardness of the abrasive material on wear.

Complex:

$$П_T = \frac{T_e}{T_q} = K_T, \qquad (9)$$

K_T – coefficient which takes into account the effect of temperature on wear.

In the third stage of the method of TSD experiment we set relationships between dimensionless complexes that serve as similarity criteria:

$$J_н = k_{wн} \cdot \left(\frac{P_{\max} \cdot f}{H_н}\right)^{x_1} \cdot \left(\frac{\delta}{\chi}\right)^{y_1} \cdot K_A^{n_1} \cdot \left(\frac{H_a}{H_H}\right)^{m_1} \cdot \left(\frac{T_e}{T_q}\right)^{z_1}; \qquad (10)$$

$$J_в = k_{wв} \cdot \left(\frac{P_{\max} \cdot f}{H_c}\right)^{x_1} \cdot \left(\frac{\delta}{\chi}\right)^{y_1} \cdot K_A^{n_1} \cdot \left(\frac{H_a}{H_c}\right)^{m_1} \cdot \left(\frac{T_e}{T_q}\right)^{z_1}, \qquad (10, a)$$

For the conditions of abrasive wear x_1 = 1 [9]; to avoid jamming between the screw and the cylinder we take constructively $\delta = \chi$; by [1] n_1 = 1; m_1 = 0,8 and z_1 = 0,1 for steel X12 (Table 1) according to the data [2]. Then:

$$J_н = k_{wн} \cdot \left(\frac{P_{\max} \cdot f}{H_н}\right) \cdot K_A \cdot K_{Hн}^{0,85} \cdot K_T^{0,2}; \qquad (11)$$

$$J_в = k_{wв} \cdot \left(\frac{P_{\max} \cdot f}{H_c}\right) \cdot K_A \cdot K_{Hв}^{0,85} \cdot K_T^{0,2}, \qquad (11, a)$$

Table 1

Chemical composition of steel X12

Steel grade	Chemical composition, %							
	C	Mn	Cr	Si	Ni	S	P	Cu
X12	2,1	0,35	12	0,2	< 0,35	< 0,03	< 0,03	< 0,3

Coefficient $k_{wв}, k_{wн}$ are found by the formula:

$$k_{wн} = \frac{U_{1н} \cdot H_{н}}{P_{\max} \cdot f \cdot L_{1н}}; \tag{12}$$

$$k_{wв} = \frac{U_{1в} \cdot H_{c}}{P_{\max} \cdot f \cdot L_{1в}}, \tag{12, a}$$

where $U_{н}$ (μm) – wear in the nitride zone on the way $L_{н}$ (μm);

$U_{в}$ (μm) – wear in the area of internal nitriding on the way of friction $L_{в}$ (μm). After the experiment, knowing $U_{1н}, L_{1н}, U_{1в}, L_{1в}$ by formulas (12) and (12, a), we find $k_{wв}, k_{wн}$.

For materials with gradient coatings the intensity of their wear is variable. Therefore, the durability of D coatings can be expressed: in linear units of the way of friction D_L:

$$D_L = \frac{h_{н}}{J_{н}} + \frac{h_{в}}{J_{в}} \quad \text{m}, \tag{13}$$

Or in hours D_t:

$$D_t = \frac{1}{3{,}6 \cdot 10^3 \cdot V} \cdot \left(\frac{h_{н}}{J_{н}} + \frac{h_{в}}{J_{в}} \right) \text{hours}, \tag{13a}$$

where V – sliding speed, m/s;

$h_{н}$ and $h_{в}$ – thickness of the nitride zone and the zone of internal nitriding expressed in meters.

In case when the value of allowable wear h is greater than the thickness of the nitrided layer, we calculate the durability of parts by the following dependencies:

$$D_L = \frac{h_{н}}{J_{н}} + \frac{h_{в}}{J_{в}} + \frac{h - h_{н} - h_{в}}{J_0} \quad \text{m}, \tag{14}$$

Or in hours D_t:

$$D_t = \frac{1}{3{,}6 \cdot 10^3 \cdot V} \cdot \left(\frac{h_{н}}{J_{н}} + \frac{h_{в}}{J_{в}} + \frac{h - h_{н} - h_{в}}{J_0} \right) \text{hours}, \tag{14a}$$

where J_0 – the intensity of wear of the basic material.

Summary

To calculate the tribological characteristics and durability of structural elements with gradient coatings and metastable phases in the material structure the following method is recommended.

We conduct calculations in the following sequence in accordance with the method of the theory of similarity and dimension (TSD):

1. We make up a list of quantities that determined with their dimensions. For materials without coating value, which is determined will be the intensity of wear:, where U – is wear and tear in μm, L – the way of friction in μm. For materials with gradient coatings obtained by nitriding, the values, which are determined will be the following figures: the intensity of wear of nitride zone – $\frac{dU_{н}}{dL_{н}} = J_{н}$ and the intensity of wear zone of internal nitriding $\frac{dU_{в}}{dL_{в}} = J_{в}$, where $U_{н}$ and $L_{н}$ – wear and the way of friction in nitride zone (μm), $U_{в}$ and $L_{в}$ – wear and the way of friction in the zone of internal nitriding (μm).

2. We make up a list of determining quantities, or the main factors affecting the abrasive wear with their dimensions. From the experimental conditions we determine pressure $P_{\max}$, coefficient of friction of sliding f, temperature of quenching T_q and wear T_e, size of the clearance δ and size of the abrasive particles χ and hardness H_a. Based on metallographic studies of experimental models we find: percentage of residual austenite in the material, microhardness of nitride zone $H_н$, microhardness of zone of internal nitriding $H_в$, microhardness of basis H_0.

3. From determining and determined quantities we make up dimensionless complexes.

4. After the experiment we set the relationship between dimensionless complexes that serve as similarity criteria (4) and (4, a).

5. Knowing the basic values of determining quantities, we conduct tests for wear. On the basis of these tests and published data we find the coefficients $k_{wв}, k_{wн}, x_1, y_1, n_1, m_1, z_1$ and intensity of wear of the friction surface by dependencies (11) and (11, a).

6. Knowing the quantity of allowable wear we find the durability of structural elements strengthened by this technology (we find by dependencies): (13), (13, a), (14), (14, a).

Deviations of calculated values of the intensity of wear and durability of materials with gradient coatings and metastable phases in their structure during abrasive wear are 11 % - 19 % of experimental data.

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Поступила в редакцію 03.03.2014

Каплун В, Гончар В., Каплун П., Матвіїшин П. **Розрахунок зносостійкості і довговічністі структурних елементів конструкцій з градієнтними дифузійними покриттями і метастабільними фазами в структурі матеріалів.**

Представлено методика розрахунку зносостійкості і довговічності конструктивних елементів з метастабільними фазами в структурі матеріалу і градієнтними покриттями на прикладі сталі Х12 після іонного азотування і наступного гартування з отриманням залишкового азотистого аустеніту.

Ключові слова: залишковий аустеніт, знос, довговічність, азотування, тліючий розряд.