Effect of Microrelief of Electrospark Coatings on Tribotechnical Characteristics

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Abstract

The stress-strain state of the coatings on the boundary between the substrate and the coating material during electrical spark doping are investigated. The influence of the micro-relief of the electrical spark coatings on the adhesion strength and wear resistance are investigated.

1 Introduction

Among the various methods of surface hardening of metals and alloys under the influence of concentrated energy fluxes, the method of electrospark alloying (ESA) is widely used. Its use helps to increase the service life, reliability and efficiency of the equipment. In turn, the reliability and resource of modern technology largely depend on the performance and service life of friction units (tribosystems) and their wear resistance. In this regard, the methods of surface hardening of materials of parts of tribosystems are becoming increasingly important and relevant.

The formation of electrospark coatings proceeds in non-equilibrium conditions due to high rates of heating and cooling microvolume of metals, which leads to the formation of a non-uniform crystalline structure containing various types of defects. Residual stresses, brittleness of the material due to the formation of a fine-crystalline structure, adhesive adhesion strength of the coating with the substrate have a significant effect on wear [1].

Considering the location bands of localized deformation bands on the sample surface at an angle to the direction of tensile forces, as well as the effect of the stress-strain state at the “coating - base” interface [2], it can be assumed that the formation of non-continuous coatings of a certain microrelief will increase the wear resistance of the surface layer [3, 4].

In the work, the stress-deformable state of the coatings with ESA, the effect of the micro-relief of the electrospark coatings on the adhesive strength and wear resistance are investigated.

2 The Calculated Model of the Stress-Strain State of the Surface Layer

As a result of pulsed thermomechanical loads during the ESA process, electro erosion and mass transfer occur on the cathode surface, i.e. a discrete relief is formed, constantly changing in the process of processing depending on temperature and mode of processing.

The model of the stress-strain state of the surface layer consists of the “coating – base” system under uniaxial tension (Fig. 1).

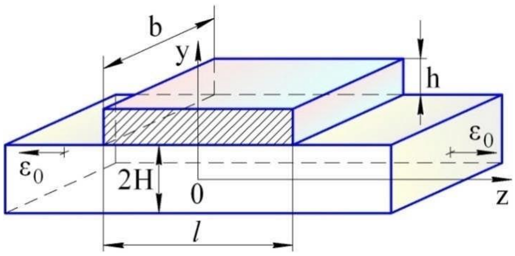

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Figure 1: Model for calculating the stresses in the "coating – base" system: h – coating thickness; $2H$ – the thickness of the base; l – the length of the coating; b – the width of the coating; ε_0 – deformation in the direction of the z axis

The base is made in the form of a plate with a thickness of 2H. On the plate form a coating thickness h, length l, width b. The destruction of the adhesive contact with significant tensile stresses can occur in the forming intermediate layer at the interface [2].

During the formation of the coating by the ESA method, internal tensile stresses arise in the surface layer and, accordingly, in the upper base layer at the joint boundary – compressive [5].

From the equilibrium condition of elements under uniaxial tension of the system, it is possible to determine the tangential stresses [6]:

to cover $$\tau_n = -h\frac{d\sigma_n}{dz}, \quad (1)$$

for the basics $$\tau_o = -H\frac{d\sigma_o}{dz}, \quad (2)$$

where σ_n, σ_o – normal stresses in the coating and substrate, h is the thickness of the coating, H is half the thickness of the base.

For the coating base system the following conditions are introduced:

$$\tau_n = -\frac{1}{b}\cdot\frac{dP_n}{dz}, \quad \tau_o = \frac{1}{2b}\cdot\frac{dP_o}{dz}, \quad (3)$$

where P_n – compressive force in one layer of the coating; P_o – tensile force at the base; b – the width of the coating across the cross section of the sample.

For the coating and the base, the deformation components along the z axis can be defined respectively as $\varepsilon_{nz} = dU_n / dz$ and $\varepsilon_{oz} = dU_o / dz$, where U_n, U_o are the displacements of the centers of gravity of the coating sections and the base, U is the displacement of the center of gravity of the section at the interface, z is the distance from the middle of the coating to an arbitrary section, $h/2$ is the coating thickness, $H/2$ is the thickness of the base (Fig. 2).

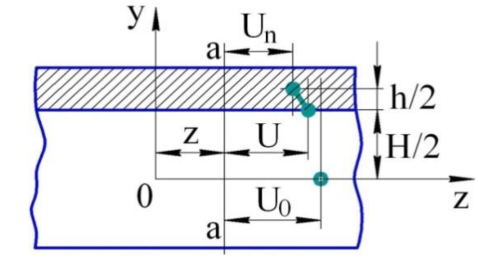

Figure 2: Scheme of movement of the centers of gravity of the sections of the base and coating

In the section $z = 0$, the tangential stresses $\tau = 0$. Accordingly, it follows from Hooke's law that:

$$\frac{\sigma_n}{E_n} = \frac{dU_n}{dz} = \frac{P_n}{E_nF_n}, \quad \frac{\sigma_o}{E_o} = \frac{dU_o}{dz} = \frac{P_o}{E_oF_o}, \quad (4)$$

where E_n, E_o – modulus of elastic of the coating material and the base; F_n, F_o – cross-sectional area of the coating and base.

From Fig. 2 we find the angles of displacement of the centers of gravity of the base and coating

$$\gamma_o = \frac{\tau_o}{\sigma_o} = -\frac{2(U_o - U)}{H}, \quad \gamma_n = \frac{\tau_n}{\sigma_n} = \frac{2(U - U_n)}{h}, \quad (5)$$

where U is displacement at the interface of the center of gravity of the stress diagram. Assuming that to $\tau_o = \tau_n$, we obtain

$$U = \frac{\sigma_oU_o / H - \sigma_nU_n / h}{\sigma_o / H - \sigma_n / h}.$$

Differentiate (4) by z:

$$\frac{dP_n}{dz} = E_nF_n\frac{d^2U_n}{dz^2}, \quad \frac{dP_o}{dz} = E_oF_o\frac{d^2U_o}{dz^2}. \quad (6)$$

Entering (6) in (3) we get

$$\tau_n = -\frac{E_nF_n}{b}\cdot\frac{d^2U_n}{dz^2}, \quad \tau_o = \frac{E_oF_o}{2b}\cdot\frac{d^2U_o}{dz^2}, \quad (7)$$

substituting (7) in (5), we find

$$\frac{d^2U_o}{dz^2} - \frac{4bL}{E_oF_o}(U_o - U_n) = 0,$$

$$\frac{d^2U_n}{dz^2} - \frac{2bL}{E_nF_n}(U_o - U_n) = 0\,, \tag{8}$$

where $L = \frac{\sigma_o}{H} \cdot \frac{\sigma_n}{h} / (\frac{\sigma_o}{H} - \frac{\sigma_n}{h})$ – coefficient depending on the voltage and thickness of the base and coating.

Subtracting the second equation from the first in (8), we get

$$\frac{d^2}{dz^2}(U_o - U_n) - K^2(U_o - U_n) = 0\,, \tag{9}$$

where $K^2 = 2bL\left(\frac{1}{E_nF_n} + \frac{2}{E_oF_o}\right)$ – coefficient depending on the geometric parameters, the modulus of elasticity of the coating and the base.

The solution of equation (9) is

$$U_o - U_n = \frac{P_o \cdot sh(Kz)}{E_oF_oK \cdot ch(Kl)}. \tag{10}$$

Substituting (10) into (8) we find

$$\frac{d^2U_o}{dz^2} = \frac{4bLP_o \cdot sh(Kz)}{(E_oF_o)^2 K \cdot ch(Kl)}\,,$$

$$\frac{d^2U_n}{dz^2} = \frac{2bLP_o \cdot sh(Kz)}{E_oF_oE_nF_nK \cdot ch(Kl)}. \tag{11}$$

From (7) and (11) follows

$$\tau_n = -\frac{2LP_o \cdot sh(Kz)}{E_oF_oK \cdot ch(Kl)}. \tag{12}$$

After transformations, we obtain the final expression for normal stresses:

$$\sigma_n = \frac{\varepsilon_o}{F_n\left(\frac{1}{E_nF_n} + \frac{2}{E_0F_0}\right)} \cdot \left[1 - \frac{ch(Kz)}{ch(Kl)}\right], \tag{13}$$

where $\varepsilon_o = P_o / E_oF_o$.

The tangential stresses at the border of the base and the coating are determined as follows:

$$\tau = \frac{\varepsilon_o K}{\left(\frac{1}{E_nF_n} + \frac{2}{E_0F_0}\right)} \cdot \frac{sh(Kz)}{ch(Kl)}. \tag{14}$$

From equation (13) it follows that the normal stresses that determine the cohesive strength of the bond between the base and the coating, depending on the position of the section under consideration, do not have constant values, but increasing from zero at the edge of the coating to the maximum value $\sigma_n \approx \sigma_в$, forming a section beyond which $\sigma_n > \sigma_в$, ($\sigma_в$ – tensile strength).

Equation (14) shows that the tangential stresses at the boundary of the base and the coating, depending on the position of the section in question, do not have constant values, but decrease from $\tau_{\max}$ at the edge of the coating to zero.

3 Experimental Results

To check the calculation of the stress state at the “base – coating” interface, experiments were conducted on a material (steel 45) with a coating applied with a T5K10 hard alloy electrode, whose adhesive strength significantly exceeds the cohesive strength.

At a certain thickness of coatings, internal stresses reduce the adhesion strength of the coating to the substrate so much that self-separation of the coating can occur. In this case, the critical thickness of the coating is determined from the condition of self-separation. When the material is operated with a continuous coating under conditions of critical deformations, the possibility of the formation of a crack on the surface of the coating, which can become a source of peaks of tangential stresses on the edges of the crack, is not excluded. As a result, delamination may occur or (under the condition of high adhesive strength) the occurrence of cracks in the base material. Consequently, in a continuous coating, all the possibilities of adhesive contact for the transfer of forces from the substrate to the coating are not used. It is limited in thickness and the material with the coating under conditions of critical deformations does not have the safety margin of the base material. It should be noted that obtaining a continuous coating in the conditions of ESA is very difficult and not always possible. Therefore, the elucidation of the effect of the microrelief of the doped layer on the stress state is an important task for ESA. Consider a uniaxial tension plate. A coating of thickness *h* and width *b* (Fig. 3) is applied on the side surfaces.

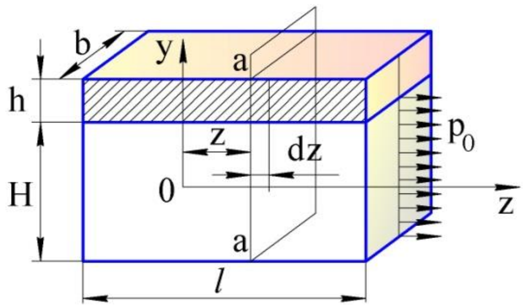

Figure 3: To the calculation of stresses in coating σ_n and tangential stresses in the zone of adhesive contact

Investigating the contact surface of the coating on steel under conditions of critical deformations, it was determined that on the surface of the metal after the destruction of the coating there were areas ("islands") firmly connected to the base. Statistical processing of the sizes of the "islands" showed that the average ratio of their width (*a*) to diameter (*D*) is 0.61 with a dispersion of 0.33 (Fig. 4).

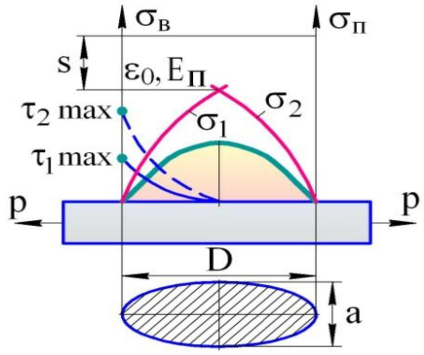

Figure 4: General view of the "island" and the distribution of normal (σ_n) and tangential (τ) stresses along its length with uniaxial tension by load P ($\tau_{1\max}$, $\tau_{2\max}$ – distribution of tangential stresses along the length of the "island", with its smooth conjugation with the base;
σ_1, σ_2 – distribution of normal stress along the "island"; *s* – margin of safety)

The step between the cracks coincides with the characteristic size, which determines the distance from the edge of the coating to the area where the stress in the coating asymptotically approaches the cohesive strength of the coating $\sigma_в / \sigma_n \to 1$.

The justification for the use of "island" coatings and the determination of their sizes can be carried out on the basis of an analysis of the distribution of normal stresses characterizing cohesive resistance [2]:

$$\sigma_n = \frac{\varepsilon_o'}{F_n\left(\dfrac{1}{E_n F_n} + \dfrac{2}{E_0 F_0}\right)} \cdot \left[1 - \frac{ch(Kz)}{ch(Kl)}\right], \tag{15}$$

where ε_o', Eo, Fo – the magnitude of the deformation, the modulus of elasticity and the cross-sectional area of the base, respectively; En, Fn – modulus of elasticity and cross-sectional area of the coating, respectively; l – 1/2 of the length of the coating; K – coefficient depending on the geometric parameters and elastic moduli of the base and coating.

Analysis of formula (13) shows that when creating continuous coatings, the normal stresses characterizing cohesive strength increase from the edge of the coating to the depth of the material, asymptotically approaching the values of the cohesive strength limit.

The size N for this coated material was determined using formula (15), given that the stress affecting the formation of cracks in the coating tends to the ultimate strength of the coating, that is $\sigma_n \to \sigma_в$. The experimental results allowed us to estimate the maximum value of the ratio $\sigma_n / \sigma_в = 0{,}95$.

For simplicity

$$M = \frac{\varepsilon_o}{F_n(1/E_n F_n + 2/E_o F_o)},$$

we determine $\frac{\sigma_n}{\sigma_в} = \frac{M[1 - chK(l - N/chKl]}{M[1 - chK(l - N)/chK(\infty)]} = 0{,}95$ under the condition that the voltage in the coating is equal to $\sigma_в$ and $l \approx N$.

Let $(l - N) \to 0$, then we have $1 - \frac{chK(l - N)}{chKl} = 0{,}95$. Transforming and logarithmically, we get

$$-KN = \ln 0{,}05; \quad N = \frac{\ln 20}{K}.$$

Based on this, a construction material with a coating has been developed, in which stresses reach $\sigma_в$ due to the small length of adhesive contact of the base the coating.

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