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Strength and Mechanism of Adhesion to the Substrate Layer while Applying Plasma Coatings in Oxidizing Environments

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Abstract: It has been examined that when an oxide layer is treated under atmospheric conditions on a treated substrate surface, in the contact zone, an oxide layer is always present. This mixed oxide layer influences the contact temperature and the adhesion strength of the particles that are being coated to the substrate surface.Henceforth the process of heating of the contact layer of surface oxides was investigated. The experimentation was demonstrated by coupling of the particles of the coating layer with the surface layer when wetting is provided by melting of the oxide layer. The conditions of the wettable contact under nonstationary heat exchange were determined depending on the thermophysical properties of the contact pair, the temperatures of the coating particles and the substrate. The wetting time was evaluated depending on the thickness of the oxide layer. The identity of the adhesion strength of the coating and the cohesive strength of the oxide layer was substantiated.

It was evaluated that for the inner surface of the coating elastic modulus and breaking stress is about 20% higher than for the external. The detected difference is related to the presence of the temperature gradient across the thickness for coating.

Keywords: Plasma coating, transient heat transfer, adhesion strength, relative deformation, cohesive strength, wetting.

INTRODUCTION

The use of plasma spray makes it possible to obtain coatings and hence creating new products when renovating the surfaces of parts. The examination of the plasma coating is determined by the physical and mechanical parameters of the coating material and the substrate. Despite the high economic efficiency of the use of plasma coatings for the restoration and hardening of parts, the strength of its adhesion and cohesive strength does not always satisfy the condition of reliable work of the part [1]. In order to develop methods for increasing the strength of plasma coating, it is necessary to select the main parameters of the technological process, which most commonly affect the quality of coatings. It is believed that such parameters are the temperature and pressure in the contact zone of the dust particles with the lining surface. For the theoretical basis of adhesion strength, the model of chemical interaction of surfaces [2] and the model of non-stationary heat transfer in the contact zone can be adopted. Since direct methods for determining the contact temperature and the temperature of the coating particles do not exist, and the theoretical models are excessively idealized, the presence of actual coating formation processes is not taken into account like, in the effect of surface oxides on the adhesion of coating particles. The mechanism of wetting in the contact zone of the sputtered particle with a substrate in the presence of surface oxides is not justified.

The present work, answers the questions to the above mentioned peculiarities. It has been established that when forming plasma coatings, it is possible for them to crack under the influence of residual thermal stresses. One of the causes of cracking is the insufficient mechanical strength of the coating. Therefore, the mechanical properties of the coating are of practical interest for the evaluation of working capacity: modulus of elasticity, cohesive strength, and also the nature of their variation in the thickness of the coating. Despite the high economic efficiency of plasma coatings' application for recovery and hardening of details, the values of adhesive strength and cohesive strength do not always satisfy the condition of reliable operation of the detail. Strength of plasma coatings applied in an air atmosphere is several times lower than the strength of a compact base material. A noticeable decrease of the mechanical strength of the coating is observed with an increase in its thickness up to 1,5 mm. Surface oxides in the contact zone have significant impact on the reduction of adhesion. Metallographic examination shows the presence of the oxide coating layer around each particle. Protective oxide layer has a more complex structure disposed outside the complete oxidation products, hematite (Fe_2O_3). It was verified that for the inner surface of the coating, elastic modulus and

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breaking stress is about 20% higher than for the external. This detected difference is related to the presence of the temperature gradient across the thickness for coating. than a layer of magnetite or chromium spinel (Fe_3O_4 or $FeCrO_4$) closer to the metal layer of wustite FeO at high temperatures.

The greatest thickness of the oxide layer is observed in the contact between the coating and the substrate. It follows that the adhesion strength of the coating depends on the strength of adhesion to the intermediate layer of oxides in the contact zones. Therefore, it is important to study the conditions of adhesion of a coating to a surface in the presence of an oxide film on it is.

FORMULATION OF THE PROBLEM

The existing model of plasma coating adhesion strength is based on the processes of chemical interaction between the surfaces in the area of physical contact. This model assumes the physical contact of the coating and substrate. In the study of this model the conditions of the surface wetting in the presence of an oxide layer on it should be taken into account. The problem is that the solid surface oxide film is not wetted by liquid metal and, therefore, the physical contact of the coating and the substrate is absent. In the absence of wetting of the surface metal oxide coating, the particles bounce off the substrate during the formation of the coating. One condition of the wetting is melting of surface oxides in the zone of contact with the particle coating [3]. The strength of adhesion in the zone of the fused contact is due to the strength of the oxide film. The values of the melting temperature of iron oxides are given in Table **1** below.

Table 1: Values of the Melting Temperature of Iron Oxides

Iron oxides	Formula	T_m, K	t_m, °C
Wustite	FeO	1647	1374
Magnetite	Fe_3O_4	1867	1594
Hematite	Fe_2O_3	1838	1565

As part of the surface, the oxide layer includes wustite and magnetite. Magnetite melting temperature is sufficiently high and exceeds the melting point of steel. When applied to steel coatings on steel substrate contact temperature is estimated 850-900°C, which is almost twice lower than the temperature of the oxide wetting. Thus, the actual problem of the study of plasma coating's adhesion conditions is associated with the refinement of the level of the contact temperature required for substrate wetting. Therefore, the aim is to determine the possibilities and conditions for achieving the wetting temperature of surface oxides by applying plasma coatings.

PHYSICAL MODEL OF THE CONTACT

It was discovered that adherence of the coating with the oxide layer depends on the contact temperature. In order to estimate the contact temperature, the model of fixed contact of the coating particles with the substrate was used. In this case, the contact temperature level is kept significantly lower than the melting point of the substrate. However, the estimates obtained did not take into account the possibility of overheating of the sputtered particles much higher than the melting point. For example, it was shown in [4] that when the anode wire is sputtered in a plasma torch, the temperature of the coating particles reaches the boiling point, rather than the melting of the metal.

The process of interaction of the coating particle with the substrate happens during the spreading and cooling of the particle. In the indicated interval, the process of chemical interaction of a particle with a substrate occurs, the velocity of which depends on the temperature in the contact zone. The duration of the chemical interaction at the maximum contact temperature is determined by the thickness of the deformed coating particle. Therefore, when choosing the particle size of the coating, it is necessary to compare the chemical interaction time and time before the particle begins to cool. It is practically important to determine the size of the deformed particle, in which the chemical interaction will provide the necessary strength of adhesion. The value of the relative strength of adhesion during the course of chemical interaction between juvenile contacting surfaces is estimated by the formula

$$\frac{\sigma}{\sigma_O} = 1 - \exp[-\frac{\nu\tau_x}{\exp(E_a / kT_K)}]. \quad (1)$$

Where σ and σ_O is the adhesion strength of the coating and the tensile strength of the substrate; ν is frequency of the individual vibrations of atoms; E_a is the activation energy of the substrate; k is the Boltzmann constant; T_K is the contact temperature between the coating and the substrate.

The magnitude of the contact temperature is determined by the simultaneous solution of the equations of the non-stationary thermal conductivity of a particle and a substrate from the condition of continuity of the non-stationary heat flux in the contact zone. Let us consider the heating of the substrate under the action of the heat flux entering the substrate upon contact with the liquid particle. To calculate the temperature field, we use the equation of nonstationary heat conductivity [5]

$$\frac{\partial t}{\partial \tau} = a \frac{\partial^2 t}{\partial x^2} , \tag{2}$$

where *t* is the temperature of the substrate, depending on the heating time *τ* and the coordinate *x* directed deep into the substrate, $\alpha = \lambda / \rho c$ is the thermal diffusivity, determined by the thermal conductivity - λ, density - ρ and heat capacity of the substrate – *c*. The peculiarity of the problem of contact heat transfer is a slight change in the contact temperature during the time during which the thermal wave propagates in the oxide layer. In this case, the nonstationarity of the process consists of expanding the heating zone, and not of increasing the contact temperature. The solution of the non-stationary heat conduct equation for this case determines the density of the heat flux in the contact area of the substrate in the form

$$q_2 = -\lambda_2 \frac{\partial t}{\partial x} = -\frac{\lambda_2 (t_k - t_2)}{\sqrt{\pi a_2 \tau}} , \tag{3}$$

where t_K and t_2 are the contact temperature and the temperature of the substrate or oxide respectively. Similarly, with the formula (3), the heat flux density in the coating particle is determined

$$q_1 = -\lambda_1 \frac{\partial t}{\partial x} = -\frac{\lambda_1 (t_1 - t_k)}{\sqrt{\pi a_1 \tau}} . \tag{4}$$

Here and below, the thermophysical coefficients of the substrate are denoted by the index "2", and the coefficients of the coating particle by the index "1", and the coefficients of the oxide layer by the index "0". It follows from (3) - (4) that the zone of the temperature field or the length of the thermal wave in the coating particle and in the substrate are determined by the formulas

$$\delta_1 = \sqrt{\pi a_1 \tau}, \quad \delta_2 = \sqrt{\pi a_2 \tau} . \tag{5}$$

On the surface of the substrate, at *x* = 0, the heating temperature under the action of the heat flux q_1 is equal to the contact temperature, the value of which is determined when equations (3) and (4) are equal, since the density of the heat flux in the contact zone of semi-bound bodies does not change

$$t_K = \frac{t_1 + t_2 \sqrt{\rho_2 c_2 \lambda_2 / \rho_1 c_1 \lambda_1}}{1 + \sqrt{\rho_2 c_2 \lambda_2 / \rho_1 c_1 \lambda_1}} . \tag{6}$$

The above formula can be used to determine the contact temperature of the coating with the oxide layer of the substrate during the time of the passage of the heat wave through the oxide layer. However, when the heat wave leaves the substrate metal, the contact temperature will change due to the difference between the thermophysical properties of the metal and the oxide. It can be seen from the formula (6), the contact temperature decreases with a relative increase in the heat capacity and thermal conductivity of the substrate.

In order to calculate the dependence of the contact temperature of the substrate with the oxide layer on the contact time, let us analyze the formula (3) and (5) for the heat flux in a homogeneous medium. Value

$$R_2 = \delta_2 / \lambda_2 \tag{7}$$

represents the thermal resistance for a single contact area of a homogeneous substrate. The thermal resistance for a layer of surface oxides of thickness δ_0 and thermal conductivity λ_0 is determined

$$R_O = \delta_O / \lambda_O .$$

The total length of the thermal wave in the oxide layer and the metal substrate is determined by taking into account the retardation time τ_0, which is equal to the time of passage of the thermal wave through the oxide layer

$$\delta_2 = \sqrt{\pi (a_O \tau_O + a_2 (\tau - \tau_O))} . \tag{8}$$

The time lag τ_0 depends on the thickness of the oxide layer

$$\tau_O = \delta_O^2 / \pi a_O . \tag{9}$$

In this case, the square of the total length of the thermal wave is equal to the sum of the squares of the lengths of the wave's constituent parts. The thermal resistance of the substrate with the oxide layer is similar to the length of the heat wave and it is determined in accordance with the condition: the square of the resistance of the substrate with the oxide layer is equal to the sum of the squares of the thermal resistances of the oxide and the sub-oxide layer

$$R_{O2} = \sqrt{\pi a_O \tau_O / \lambda_O^2 + \pi a_2 (\tau - \tau_O) / \lambda_2^2} \,. \tag{10}$$

With the thermophysical characteristics of the oxide and the substrate metal being identical, the formula (10) coincides with the formula for the thermal resistance of a homogeneous substrate (7). Then the formula (3) for the heat flux of the substrate with the oxide layer takes the form

$$q_2 = -\frac{t_K - t_2}{R_{O2}} \,. \tag{11}$$

Comparing (11) with the heat flux density of the particle of the coating (4), we find the formula for the contact temperature in the form

$$t_K = \frac{t_1 + t_2 B}{1 + B} \,, \tag{12}$$

where B is the ratio of the thermal resistances of the coating particle and the substrate to the oxide layer. Taking into account the dependence of δ_1 and R_{02} on time according to (5) and (8), we obtain the formula for B as a function of the contact time τ, for $\tau > \tau_o$

$$B = \frac{\delta_1 / \lambda_1}{R_{O2}} = \frac{\sqrt{\tau / (\rho_1 c_1 \lambda_1)}}{\sqrt{\tau_O / (\rho_O c_O \lambda_O) + (\tau - \tau_O) / (\rho_2 c_2 \lambda_2)}} \,. \tag{13}$$

For the initial moment of contact, for $\tau < \tau_o$, the thickness of the temperature layer in the substrate is smaller than the thickness of the oxide layer and the formula (13) takes the form

$$B = \frac{\sqrt{\rho_O c_O \lambda_O}}{\sqrt{\rho_1 c_1 \lambda_1}} \,. \tag{14}$$

In the absence of an oxide layer ($\delta_o = 0$, $\tau_o = 0$), or if its thermophysical properties are identical with the properties of the substrate, substitution of the formula (13) in (12) leads to the formula (6), which confirms the reliability of the use of (10) for defining the resistance of the substrate with the oxide layer. The formulas (12) - (13) give the dependence of the change in the contact temperature from the contact time for $\tau > \tau_o$.

RESULTS AND DISCUSSION

In calculating the contact temperature, it was assumed that the heating temperature of the coating particles had reached the boiling point. Estimations of the contact temperature were made when a steel coating was applied to a steel substrate. It was taken into account that the values of thermophysical coefficients in the solid and liquid states near the melting point [6] differ from each other, Table **2**. For example, the density of the metal during melting is reduced by 10%. The thermal conductivity decreases by a factor of about 2, and the heat capacity increases by 10-20%. The data of the literature sources differ from each other by 15-20%. Therefore, the calculation error was also close to 20%. In Table **1**. Thermophysical coefficients for iron oxide in the solid state are also shown [7-9], which show that the thermal conductivity of the oxide is 3 to 4 times lower than that of liquid steel.

The estimated evaluation of the contact temperature when applying a coating of Hp65G wire on a substrate of St45 steel and on a substrate with an oxide layer, depending on the initial temperature of the substrate, is given in Table **3**. It is of interest to measure the contact temperature on the surface oxide layer, which is much

Table 2: Thermophysical Coefficients for Liquid Particles of a Steel Coating and for a Steel Substrate and an Oxide Layer - in a Solid State Near the Melting Point

	ρ_s kg/m^3	ρ_l kg/m^3	λ_s W/m K	λ_l W/m K	c_s J / kg K	c_l J / kg K	t_m, °C	t_b, °C
Fe	7760	7000	29	17	662	710	1535	2735
Fe_3O_4	5240		5		783		1594	

Table 3: The Values of the Contact Temperature as a Function of the Temperature of the Substrate at the Initial Moment of Contact at $\tau < \tau_o$ for the Coating Particles Heated to the Boiling Point

	Coating	Base coat	t_2, °C			
			0	50	100	150
t_c, °C	Fe	Fe	1230	1257	1285	1312
	Fe	Fe_3O_4	1830	1840	1853	1870

higher than its melting point. The result obtained explains the appearance of wetting of the surface oxides at the moment of adhesion to the coating particle.

An important value is the temperature of the coating particles, at which the phenomenon of wetting of the substrate occurs. According to the calculation of the formula (10), to wet the substrate with an initial temperature of 100 ° C, when the oxides are melted, the temperature of the coating particles above 2330 ° C is required.

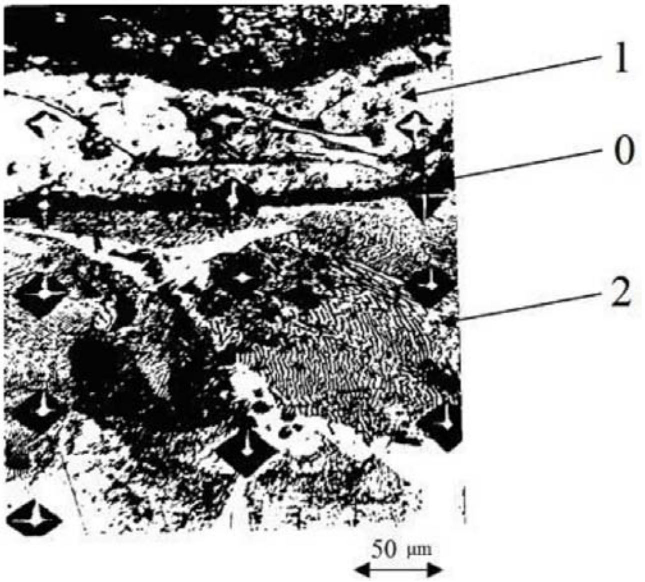

Figure 1: Microscale of the coating-substrate contact (magnification 300) obtained by shot peening the substrate. The coating is Hn-65G (above), the substrate is steel St45 [10].

To estimate the lifetime of the largest contact temperature, we used the formula (9). The thickness of the oxide layer on the substrate was determined using a microsection photo of the contact, Figure **1**. With an increase of 300 and the thickness of the image of the oxide layer in the photo, 2 mm, the actual thickness of the oxide layer was 7 μm. When the thermal diffusivity of the oxide is $\alpha = \lambda / \rho c = 4,6 \cdot 10^{-6}$ m^2 / s, the time for the passage of the thermal wave through its thickness, according to (9), is $3,4 \cdot 10^{-6}$ s. In the indicated time interval, the temperature of the oxide layer is constant and corresponds to the data in Table **2**. After this interval, the temperature field propagates deep into the substrate metal, where the thermal conductivity is higher. In this case, the contact temperature decreases asymptotically approaching the contact temperature for the juvenile metal substrate, which, according to Table **2** is approximately six hundred degrees lower. Thus, the presence of an oxide film on the surface of the substrate leads to an increase in the contact temperature, up to the melting point of the film. In this case, the wetting of the substrate oxides with the coating particles takes place, which is necessary to ensure physical contact. The change in contact temperature over time is given in Table **4** for an initial substrate temperature of 100 ° C at coating particle temperatures of 2735 ° C, 2500 ° C and 2300 ° C.

The temperature of the coating particles 2330 °C serves as the boundary temperature of the melting of the oxides. The lifetime of the liquid phase of the oxide at the temperature of the particles of the coating 2500-2735°C is approximately (10-20) μs, depending on the temperature and thickness of the deformed particles, which is sufficient for the chemical reaction to occur in the presence of physical contact. The value of the relative strength of the particles adhesion to the substrate depends on the activation energy of surface oxides. The activation energy of magnetite, given in the handbook [11], is 0,35 eV. The estimate shows that under the conditions under consideration, the bond strength of the particles is equal to the strength of the substrate. It should be noted that the presence of a chemical interaction at the same contact time occurs at contact temperatures half that of those used here [1]. In this case, the strength of the contact zone is not inferior to the strength inside the oxide layer and it is equal to the cohesive strength of the oxide layer of the substrate. The existing bond strength of Fe-Fe plasma coatings is 29-35 MPa [1,2] and it is close to the reference value of the tensile strength of wustite, which is 29 MPa, which confirms the match of these values.

Table 4: Dependence of the Contact Temperature on the Contact Time at a Coating Particle Temperature of 2735 ° C, the Substrate Temperature of 100 ° C, and the Thickness of the Oxide Layer on the Substrate is 7 μm

τ/τ_0		0	1	2	3	5	9	17	33
τ, μs		0	3,4	6,8	10,2	17	30,6	58	113
t_c °C	t_1= 2735	1853	1853	1833	1733	1695	1600	1530	1500
	t_1= 2500	1693	1693	1675	1583	1549	1462	1398	1371
	t_1= 2300	1558	1558	1541	1457	1425	1345	1287	1261

Therefore, the adhesion strength of the coatings under the condition of melting and wetting of the contact zone is practically equal to the minimum cohesive strength of the oxide layer of the substrate. Increasing the strength of adhesion of atmospheric coatings is possible by using corrosion-resistant coatings when applying a protective atmosphere of inert gases and performing other measures that reduce the influence of the oxide layer of the substrate on the adhesion strength.

MECHANICAL CHARACTERISTICS OF PLASMA LAYER

The process of plasma spraying on a cylindrical surface of the rotating part is shown in Figure **2**. The powder particles were heated in the plasma jet to the temperatures being substantially above the melting point and the particles stick to the roughened surface of the part forming a coating layer. The roughness of the coating measured by the profilometer was 40 μm.

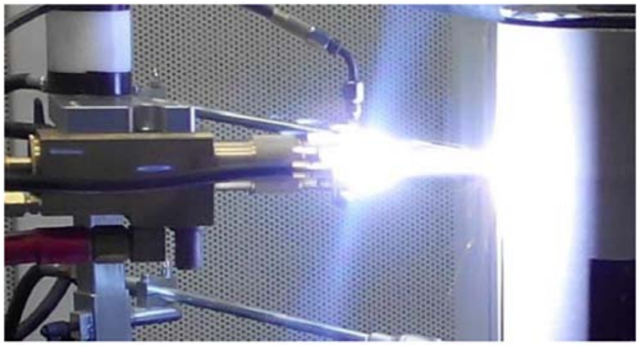

Figure 2: Application of a powder plasma coating to a rotating surface.

Powder coating was carried out on Metko 9MVM installation with the plasma torch current of 450 A, the arc voltage of 50 V, the spraying distance of 100 mm, the argon flow rate of 42 liters / min. Coating microsection presented in Figure **3** shows the presence of internal defects such as porosity and existence of oxide layers both on the boundary with the base, and between the coating layers. The presence of these defects leads to a significant reduction in the cohesive strength compared to the strength of a compact material.

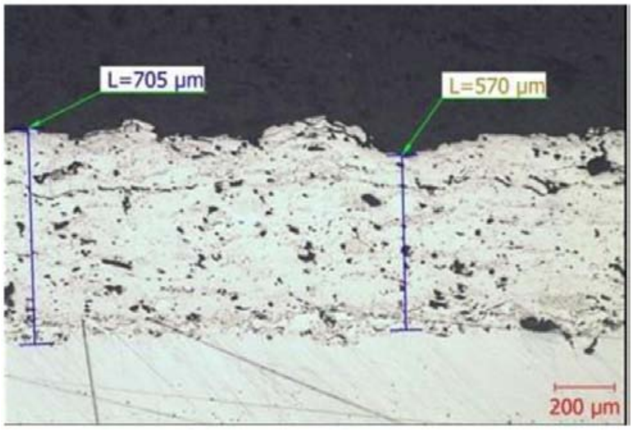

Figure 3: The microstructure of chromium-nickel coating.

In this work considers the change of the modulus of elasticity and tensile strength through the coating thickness during the bending through the angle of exfoliated plasma sample with 1,46 mm thick coating. For this purpose, bending tests were carried out both on internal and external coating layers. The measurements of moment of the free end of the rod were carried out depending on the applied transverse force. Application of force during the test of the coating is shown in Figure **4**.

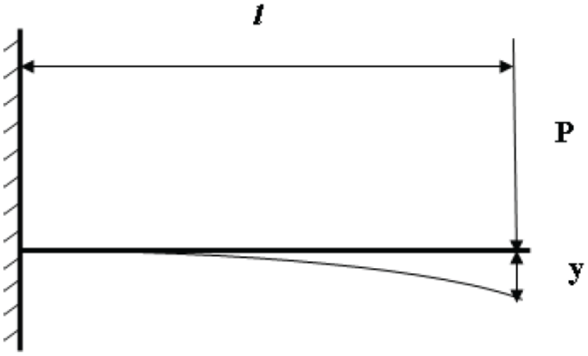

Figure 4: Loading diagram of the coating during bending.

The dependence of the movement of the operating transverse force is determined by Maxwell's - Mohr formula

$$y = \frac{Pl^3}{3EI'} \tag{15}$$

where *P* – transverse force applied to the end of the rod with length *l* , *E* – modulus of elasticity, *I* – moment of inertia of sample cross section.

The use of the formula (15) allows determining the value of sample elasticity modulus depending on the movement of the free end

$$E = \frac{Pl^3}{3yI'}. \tag{16}$$

In order to determine the maximum normal stresses on the sample surface the following formula is used while bending through the angle

$$\sigma = \frac{Pl}{W'} \tag{17}$$

where $W = bh^2/6$ - modulus of resistance of sample square section, b and h – section width and thickness.

The value of the relative maximum deformation was determined on the basis of the Hooke's law

$$\varepsilon = \frac{\sigma}{E}. \quad (18)$$

Considering the above-mentioned formulas (15) - (18), the maximum relative deformation value is determined depending on the movement of the free end of the rod:

$$\varepsilon = \frac{3}{2}\frac{hy}{l^2}. \quad (19)$$

Determination of the mechanical properties on both outer surface and inner surface of the coating is of interest. It is known that the compressive strength of brittle materials exceeds the tensile strength several times. Such materials include plasma coating. Therefore, the destruction of the coating was determined by the strength of the stretched layers. The effect of the heterogeneity of the mechanical properties of the coating was evaluated by comparing the results of tensile tests of both internal and external surfaces.

Thus, the modulus of elasticity, relative deformation and normal stress on the sample surface were determined by measuring the movement of the free end of the rod under the action of force P. Breaking stress was determined by the parameters of the sample fracture.

One possible cause of the coating cracking may be the increase of the residual stresses when the surface is overheated during the plasma spraying process. Since the coating has tensile residual thermal stresses, not only the strength of adhesion to the base, but also the modulus of elasticity and cohesive strength, and also the nature of the changes in height of the coating are of great interest for the evaluation of the efficiency.

Tensile and compression test and bending test are used among the existing methods for measuring the mechanical properties. Tensile and compression test of the exfoliated coating is assumed to work by averaging the mechanical properties of the coating along the cross section of the sample. But this method of measurement does not allow identifying the difference of mechanical properties on the outer and inner surfaces. In contrast to this method, the use of the sample bending test allows finding the difference of mechanical properties at these surfaces.

The aim was to estimate the nature of changes in the mechanical properties of the coating through the layer height by means of a bending test, and development of recommendations for the prevention of the destruction of coating with the thickness greater than 1,5 mm.

Tests of chromium-nickel (AP-NiCr15Si3B2) coating exfoliated self-fluxing coating were carried out by measuring the movement of the free end of the sample under an applied transverse force. Movement measurement was performed using calipers. The maximum amount of movement during the sample breaking was 19,5 mm. Sample parameters were: sample width is $13{,}2 \cdot 10^{-3}$ m; sample thickness is $1{,}46 \cdot 10^{-3}$ m; length is 0,1 m when tensile test of the

Table 5: Characteristics of the Bending Deformation under Tension of the Internal Surface of the Coating

No.	P, N	M, N·m	y, 10^{-3}m	σ, MPa	E, 10^4 MPa	ε, 10^{-3}
1	1	0,1	2,0	21,3	4,88	0,44
2	2	0,2	3,8	42,6	5,13	0,91
3	3	0,3	5,5	63,9	5,32	1,20
4	4	0,4	7,3	85,3	5,34	1,59
5	5	0,5	9,0	106,6	5,42	1,97
6	6	0,6	10,6	127,9	5,52	2,32
7	7	0,7	12,0	149,3	5,69	2,63
8	8	0,8	13,2	170,6	5,90	2,89
9	9	0,9	15,5	191,9	5,66	3,39
10	10	1,0	17,0	213,2	5,73	3,72
11	11	1,1	19,5	234,5	5,49	4,27

Table 6: Characteristics of the Bending Deformation under Tension of the Outer Surface of the Coating

No.	P, N	M, N·m	y, 10^{-3}m	σ, MPa	E, 10^4 MPa	ε, 10^{-3}
1	1	0,09	2,0	19,2	3,55	0,54
2	2	0,18	3,5	38,4	4,06	0,95
3	3	0,27	5,0	57,5	4,26	1,35
4	4	0,36	6,0	76,8	4,73	1,62
5	5	0,45	7,5	95,9	4,73	2,03
6	6	0,54	9,0	115,1	4,73	2,43
7	7	0,63	10,8	134,3	4,60	2.91
8	8	0,72	12,5	153,5	4,54	3,38
9	9	0,81	14,0	172,7	4,56	3,88
10	10	0,9	15,5	191,9	4,58	4,19

internal surface and 0,09 m when the tensile test of the exterior surface. Fraction sizes of the powder are 40 - 100 micrometers. The value of the modulus of elasticity was determined according to the formula (16). In order to assess the maximum tensile stress in the critical section in the sample fixing point, the formula (17) was used, and the elongation of the surface layer in the cross section was found from the formula (19). The results of measurement under tension of the coating's inner surface are given in Table **5**.

Based on the obtained results, under tension of the inner part of the coating, Hooke's law is preserved, e.g., the proportionality between stress and relative deformation up to a fracture. The value of the coating's modulus of elasticity is at average of $5{,}6 \cdot 10^{10}$ Pa, which is about 4 times less than the modulus of elasticity of a solid material and is consistent with the measurements of other authors [2].

In order to estimate the anisotropy of properties throughout the coating's height, similar measurements were made under tension on the outer surface thereof. The results of measurements of characteristics of material under tension are shown in Table **6**. Comparing the characteristics of Tables **4** and **5**, it should be noted that the tensile strength and modulus of elasticity of the outer part of the coating is about 20% lower than for the inner part being adjacent to the coating base surface. This difference is explained, apparently, by the difference of the temperature conditions of the formation of the coating and the occurrence of residual thermal stresses therein [12-16].

The external coating layers being heated to a higher temperature are stretched upon cooling more than the inner coating layers, causing microcracks and worsening of the mechanical properties such as tensile strength and modulus of elasticity.

When spraying on a rigid base, the value of the residual thermal stresses in the one-dimensional approximation is estimated by the formula

$$\sigma_t = \alpha\, E\, \Delta\, t, \tag{20}$$

where α =1,3 10^{-5} degrees^{-1} – coefficient of nichrome thermal expansion; Δt - difference between the temperature of the coating layer under consideration and the average temperature of the base surface. Since the heat flux is applied to the coating surface on the outside, the temperature difference Δ*t* for the outer layer will be greater than for the inner layer, causing additional tensile stresses on the outer surface upon cooling. According to (20), the maximum difference of temperature between the coating outer layer and the base surface that is sufficient for the occurrence of breaking stresses with some impact of the voltage values and the modulus of elasticity, is

$$\Delta\, t = \frac{\sigma}{\alpha E} = 306\ ^\circ C \tag{21}$$

In the contact zone of the coating with the base surface the temperature difference Δ *t* will be less due to the cooling effect of the base surface. Therefore, the residual thermal stresses for the inner layers of the coating will be significantly lower.

CONCLUSIONS

1. It is verified that due to the low thermal conductivity of the oxide upon contact with the

coating particle, the temperature on the surface of the oxide film of a steel substrate is significantly higher than in the absence of oxides. Level of contact temperature significantly exceeds the melting point of the oxide film, which is a prerequisite for wetting and ensuring physical contact with the coating particle.

2. The wetting conditions of the oxide layer of the substrate with the initial temperature of 100° C correspond to the temperature range of the particles (2735-2330) ° C, which is observed during arc spraying of the anode wire in the plasma torch.

3. The melting and wetting time of the oxide layer of the substrate is 7 μm thick in the range (8-10)·10^{-6} s, which under considered a sufficient condition for the complete course of the topochemical reaction of the bond between the coating and the oxide layer.

4. At coating particle temperatures (2330-2735) ° C, the adhesion strength of Fe-Fe coatings is identical to the tensile strength of wuestite as the least durable component of the oxide layer of the substrate.

5. Due to chromium-nickel coating being exfoliated from the base surface during bending tests, the values of modulus of elasticity, tensile strength of the coating and the relative maximum tensile deformation from both the outer and the inner surface adjacent to the substrate side were obtained. It was found that the tensile strength and modulus of elasticity on the inner surface of the coating was greater than about 20% of the corresponding value on the outer surface of the coating.

6. The reason for the difference of mechanical properties on outer and inner surfaces of the coating is, apparently, due to existence of a temperature gradient along the height of the coating during its application, which increases the thermal residual stresses on the outer surface in comparison with the inner surface of the coating.

7. The values of the coating breaking stress σ = 190-230 MPa and the elastic modulus E = 45-56 GPa under breaking relative deformation were obtained. Lower values of breaking stress and modulus of elasticity are related to the outer side of the coating. It should be noted that the adhesive strength of coatings with base surface is 40-45 MPa, which is 5 times less than the breaking stress of the coating.

8. In order to prevent overheating of the coatings for more than 250 °C and occurrence of breaking thermal deformation, the spraying thermal mode should be changed. When spraying the coating of thickness greater than 1 mm, a break of 10-15 minutes after the application of a layer with thickness of 0,3 mm should be made for the coating cooling to the temperature of the detail. Another method of reducing the temperature of the coating is to increase the spraying distance up to 200 – 250 mm.

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