Steel surface modification with plasma spraying electrothermal installation using a liquid electrode

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Abstract. Recently, much attention has been paid to different processes using low-temperature plasma, and in particular, the process of plasma spraying. Despite the fact that the plasma spraying method has been established for a relatively long time, there are several unsolved issues in this field that are associated with the choice of the optimal spraying modes. It is connected with the fact that the development of optimal spraying process modes is a rather difficult task, since the problem of creating an optimal design for the plasmatron is not solved yet. In this article the technological plasma plant with liquid electrode is discussed, which provides a plasma spray with a temperature up to 5000°C and lengths up to 100 mm. Engineered installation allows to carry out plasma spraying of steel surface. The process and parameters of plasma spraying optimal modes are examined in the article.

1. Introduction
The hardening and corrosion protection problems of new-produced parts and recovery problem of worn parts surfaces are the problems of today, because the industry is forced to replace complex, labor-consuming and expensive new parts and connection joints for the further machines operation until complete recourse has being produced [1].

One of the most perspective ways of hardening and protecting the parts surfaces is plasma spraying [2, 3], especially for machine parts operating at high temperatures. Deterioration can reach 1 – 1.5 mm. As these parts are complex-alloyed, the conventional restoration methods of welding, overlaying and electroplating are prohibitive because of defects in the weld zone, the impossibility of welding, distortion, structural changes in the metal, the duration of the deposition electroplating process, etc. [4, 5]. All these disadvantages are absent during surfaces spraying: it can be applied to various refractory materials, it can be sprayed on different materials, the coating can be applied both to large and to limited sections, the possibility of spraying the coating thickness of 2 mm and multilayer coatings, basic light heating, no structural changes in basic, equipment simplicity [6].

2. The experimental installation
Functional diagram of the experimental electrothermal installation (Fig. 1) intended to produce electric charge [7] at atmospheric pressure consists of a power supply system, equipment for storing, cleaning, feeding and regulating electrolyte; changeable electrolytic cells – basins; installation operation monitoring and control equipment and apparatus for measuring the characteristics of

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Electrical discharges, thermal processes parameters and effects of plasma discharge electrolytic electrode on solids.

**Figure 1.** Functional chart of the experimental electrothermal installation
1 - power supply; 2 - current supply; 3 - grounding switch; 4 - current-carrying plate; 5 - container for electrolyte storing; 6 - electrolytic cell; 7 - pointing device; 8 - exhaust hood; 9 - solid metal electrode; 10 - valves; 11 - check valve; 12 - coil; 13 - pump; 14 - fan; 15, 16 - pipe cooler; 17 - thermometer.

Electric discharge occurs between the liquid and the solid (metal) electrodes in a range of interelectrode distances $l = 1 \div 100$ mm, the current $I = 10 \div 100$ A, the voltage $U_p = 40 \div 300$ V. As electrolytic electrode process water, mortars of NaCl, CuSO$_4$ of different concentration, etc. were used.

**Figure 2.** A device with the discharge chamber in the form of a truncated hollow cylinder for producing the plasma jet

The workflow where a powder chamber in the form of a truncated hollow cylinder is used as a metal electrode is shown in Fig. 2. The electrical discharge is produced between the bottom edge of the metal and the flow of the electrolytic electrodes. When the metal electrode surface temperature reaches a certain value (about 50°C) plasma jet occurs through the interior channel of the discharge chamber. The length of this jet essentially depends on the discharge current $I$, the interelectrode distance $l$, the type of the discharge chamber and the flowing electrolyte and metal electrode temperature. To maintain optimum surface temperature of the metal electrode cooling with tap water is used.
3. Results and their discussion

Gas (argon, nitrogen, air) passes through a burning arc between two electrodes (the electrode, the electrolyte and the copper nozzle). Due to the high energy of the burning arc gas atoms lose electrons from their outer shells. The result is an ion-electron gas or plasma. Coming out of the nozzle copper electrode at high speed electrons fill their places in orbits around atoms. As a result, energy is released. The temperature of the plasma spray reaches 3000 – 5000˚C. In the zone at the outlet of the nozzle sprayed material is supplied into the plasma spray in powder form. The iron oxide powder Fe$_3$O$_4$ was the material for the deposition. As a result the spraying material is heated to the melting accelerates and applied to the surface of the workpiece. Adhesion strength of coatings with the basic amounts 20 MPa.

In the sputtering process it is necessary to control the thickness of the sprayed layer, which for plasma coating is 0.1 – 2 mm. Parts surfaces which are not to be plasma sprayed, must be protected by the special protective equipment.

Plasma coatings studies on wear resistance were conducted at a temperature of 800˚C, and showed that plasma coatings have wear resistance of 1.5 – 3 times higher than the wear resistance of the substrate made of special steels and alloys.

The effect of coating thickness on the coating strength of the iron oxide in the separation of the underlayer is shown in Fig.3. Reduced adhesion of coatings with increasing thickness is due to the accumulation of residual stresses in sequential deposition of layers.

![Figure 3. The adhesion strength dependence on the iron oxide coating thickness](image)

When spraying the powder Fe$_3$O$_4$ on the thickness of 1.0 – 1.5 mm, the influence factors of the coating process on the cleavage strength are recognized. With plasmatron current increasing, the strength decreases due to increased oxidizability of the coating material and the base and residual stresses sharp increase. The increasing of the distance and the iron oxide particles flight time increases the strength. The spraying distance reduction less than 50 mm is unpractical because of overheating of the sprayed coating and peeling. The plasmatron power increasing improves bond strength due to the increase in enthalpy of the particles.

An important factor determining the strength of adhesion of plasma coatings and other physico-mechanical properties is the quality of atomization of the sprayed particles. With powder materials plasma spraying, the intensive heat transfer of the powder particles, which are in the plasma flow is occurred, but the residence time of the particles in it are limited. Since the propagation of heat in the particles of the material deposited by the plasma is going on due to the thermal conductivity, the particles dimensions of the sprayed powder are important for adhesion. Large particles do not have time to melt during the residence time in the plasma spray and impinge on the surface at weakly plastic state, thereby worsening the quality of the coating. Fine particles impede powder supply into the nozzle, clog the nozzle and are rapidly cooled on the way to the product losing speed.
The optimum size selection of the powder depends on many conditions. The particle diameter can be obtained from the heat equation [8] \( \frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \), wherein \( \alpha = \lambda c/\gamma \) – the thermal diffusivity coefficient; \( \lambda \) – thermal conductivity; \( c \) - specific heat; \( \gamma \) - density; \( \tau \) – heating time of the powder.

The solution of the equation in the criterion form

\[
(T_m - T_1)/(T_m - T_2) = f(F_0),
\]

where \( T_m \) – the particles melting temperature; \( T_1 \) – the particle center initial temperature; \( T_2 \) – the final temperature of the particle center; \( F_0 \) - Fourier criterion \( (F_0 = 4\alpha \tau/r^2); \) \( r \) - the radius of the particle.

The decision criterion equation at \( T_2 = 0.9T_m; \) \( f(F_0) = 0.1; \) \( F_0 = 0.3 \)
gives the maximum value of the powder diameter

\[
d = 4\sqrt{\frac{a\tau}{0.3}}.
\]

The calculation of the equation (1) for iron oxide gave the diameter value of 100 \( \mu \)m.

Granulated powder composition is to be uniform. With a wide range of particles dimensions the quality and adhesion of the coating deteriorate significantly. This is due to the uneven heating of different granulation powder.

Spraying angle affects the adhesion strength. At angles close to 90˚, the adhesion strength is deteriorating due to the reduction of particle velocity by the reflected airflow. At angles smaller than 40-60˚, there is a reflection of the particles of the sputtered material.

The results of measuring the peel strength of plasma coatings deposited (sprayed) at different angles are shown in Fig.4.

The greatest strength of adhesion of iron oxide coatings is achieved by applying an angle 60˚. This is due to the fact, that with the angle decreasing from 90˚ to 60˚, the resistance of the gas spray decreases, and consequently increases the speed of the particles by collision with the surface, which leads to a better adhesion of coatings to it. As seen from the figure, the adhesion coating strength at a spray angle of 60˚ 2.5 times higher than at 90˚. In plasma spraying angle of less than 45˚ is unacceptable, because of the particles large slip, and hence, poor fixing them on the surface.

To optimize the process of plasma deposition of iron oxide on the metal substrate, the regression dependence of the adhesion strength on certain input parameters is determined. To do this, the method
of planning multifactor experiment was used [9]. Since it is impossible to take into account all of the input parameters in the study, the most important parameters: the power of the discharge current (I), the magnitude of distance from the powder inlet to the substrate (h), the plasma gas flow rate (Q), and processing time (τ) were chosen for a selected sputtering method and installation. The following parameters: d - coating thickness and ρ - density of the coating were selected as the output value of optimization.

Mathematical treatment of the experimental results by using the least squares method [10] yielded the regression equation in the following form:

\[ d = y = 50.69 + 3.31x_1 - 5.22x_2 + 6.16x_3 + 5.78x_4 - 0.18x_2x_3 + 7.31x_3x_4 \]

\[ ρ = y = 2.92 + 0.28x_1 + 0.27x_3 - 0.34x_4 + 0.29x_1x_4 + 0.14x_2x_4 + 0.11x_3x_4 \]

Thus, the function (dependences) obtained can be used to determine the desired operating mode, as well as for process control.

4. Conclusions

These results suggest that to improve the adhesive strength comprehensive theoretical and experimental studies that allow to reveal the mechanism of a durable adhesive contact formation are needed. The use of multivariate experiments planning methods enables to optimize the deposition process in order to obtain maximum adhesion strength.

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