Dual-program impulse modulation of plasmatron power in processes of plasma spraying

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Abstract. On the basis of analysis of plasma coating processes the influence of electrical parameters modulation of the remote arc on the temperature field in the "coating-base" system in the local scale, proportional to the diameter of the arc binding spot to the surface, and in the macro scale of sprayed surface is valued. Dual-program impulse modulation of plasmatron power, providing uniform distribution of the coating connection strength with the substrate layer based on uniform distribution of surface thermal activation and local zones of coating penetration on the sprayed surface is offered.

Keywords: Plasma, arc plasmatron, coating, hardening, mathematical model, modulation

1. Introduction
The analysis of ways of improvement of plasma spraying and hardening of coatings shows, that traditional ways of its development on the basis of modifications of stationary processes have reached the limits of the appreciable increasing of their efficiency and for enhancement of the electric arc plasma spraying technology it is advisable to use the method of parameters dynamization. The latter includes plasma spraying and hardening of coatings (PSHC) with using of the electrical parameters modulation of the remote arc (straight arc) [1].

The objects of PSHC with the electric parameters modulation of a remote arc of plasmatron there were thermal and physical-mechanical processes in the system of ”remote arc – coating – basis”. The influence of the electric parameters on the temperature field of the sprayed surface has two space-time scale aspects – local and general [2]. In the aspect of local impact on the coating for increasing the strength of the coating connection with the base it is necessary to provide discretely distributed local zones of penetration of the surface to the transition zone of "coating-substrate". In the aspect of the whole surface scale it is necessary to provide minimization of the temperatures scatter on the surface profile of the base and uniformity of its temperature field.

The task of the work is to determine the parameters of the PSHC, ensuring optimal coating strength with high uniformity of the temperature field of the base surface.

2. Research methods
The objectives were solved by mathematical modelling and experimental investigations of the temperature distribution and coating properties at electric parameters modulation of the remote arc of the
plasmotron [2]. The procedural framework of theoretical researches was scientific bases of heat welding processes theory, methods of numerical mathematics (method of finite differences), present-day graphic and numerical systems for electronic computing machines.

The temperature of the cylindrical sample with the coating was determined by pyrometric method and by the thermocouples. The strength of the coating connection with the base was determined on the samples by the shear method, and fatigue characteristics of the coated samples - on the fatigue-testing machine [3].

3. Calculation dependencies and Results of Researches

The calculation of the temperature field on the coated base surface was performed on the mathematical model base presented in the work [2]. Weighted average value of the heat flow \( q_{imp} \) to the coating, which is necessary for its local penetration and for maximum temperature \( T_{\max} \), equal or greater than the melting temperature of the coating material, was performed with the dependency, \( W \):

\[
q_{imp} = 4.25 \cdot V \cdot c_p \cdot h^2 \cdot T_{\max} / \varepsilon,
\]

where is \( q_{imp} = \Delta q_{imp} \cdot \tau_{imp} \cdot \nu_{imp} \cdot V \) – speed of movement of the plasmotron, m/s; \( c_p \) – volumetric heat capacity of the coating material, J/(m\(^3\) \cdot K); \( T_{\max} \) – melting temperature of the coating material, °C; \( r_0 \) – radius of the arc binding spot to the coating, m; \( h \) – depth of coating to the transition zone, m; \( \Delta q_{imp} \) – amplitude of power pulses, W; \( \tau_{imp} \) – pulse duration, s; \( \nu_{imp} \) – pulse frequency, Hz; \( \varepsilon \) – accounting factor of the heat source distribution:

\[
\varepsilon = 2 \cdot \frac{h}{r_0} \left( \sqrt{\frac{(h/r_0)^2 + 1 - h}{r_0}} \right).
\]

Temperature field away from the heat source \( T_\Sigma \) for cylindrical bodies, sprayed on a screw line, was determined by the expression based on the theoretical positions of work [4]:

\[
T_\Sigma (r, z, \Theta, t) = \frac{q_n}{R^2 \cdot c_p} \cdot \frac{1}{\sqrt{\pi}} \sum_{n=1}^{N} \frac{\Phi(\rho, \tau_n)}{\sqrt{\tau_n}} \cdot \exp \left[ -\frac{\xi^2 \cdot n^2}{4 \cdot \tau_n} \right],
\]

where is \( q_n \) – lineal energy, \( q_n = \frac{q}{V_{c}} \), J/m; \( q \) – thermal effective power of the plasmotron, W; \( \tau_n \) – non-dimensional complex that characterizes the time as the function of the revolutions number \( n \) of the cylindrical body, \( \tau_n = \frac{2 \cdot \pi \cdot n}{R \cdot V_{c}} \); \( N = 1, 2, 3 \), and so on; \( \xi \) – non-dimensional complex that characterizes the pitch of spraying, \( \xi = \frac{H}{R} \); \( H \) – pitch of revolutions, m.; \( R \) – radius of the cylinder, m; \( \Theta \) – angular coordinate, rad.; \( \Phi(\rho, \tau_n) \) – function that characterizes the process of heat propagation on the radius of the cylinder; \( V_{c}, V_{c} \) – respectively axial and circumferential speed of the heat source, m/s;

Adjusting the power of the remote arc by means of pulse modulation allows in the aspect of scale of the whole surface to provide minimization of temperatures scatter on the profile of the base surface and uniformity of its temperature field. This is confirmed by the results of calculations for cylindrical parts when spraying on a screw line using the solution (3) (Fig. 1). In the graph of the base temperature dependence \( T_\Sigma \) from the distribution of the average weighted power amplitude \( q_{imp} \) and rotation speed \( n \) it appears that except the first coil temperature differential in the regulation of power pulse is 2-7% of the temperature average level. For the first coil, the value of average weighted impulse power modulation \( q_{imp} \) should be at 1...15 multiple of values \( q_{imp} \) higher than on other coils. Because of this during the first coil it is necessary to change the power \( q \) from 75 kW to 1 kW, and that requires high synchronization of the process of operation, so on the first coil it is advisable to use preheating of the surface by plasma jet without the plasmotron feed.

The temperature differential level from the second coil is significantly lower in comparison with
traditional method of using the preheating by plasma jet without longitudinal feed of plasmatron along the cylindrical part. It is 10-20% of the average level, i.e. it is 80-180 °C less than using the traditional method. Decreasing the temperature differential on the surface of the part allows to lower the difference in temperature deformations on the different parts of the surface, creates the conditions for uniform distribution of structure and physicomechanical properties of a coating and a base. Applying the power modulation of the remote arc when spraying on the profile surfaces even more effective. In particular, it refers to the details of the wedge-shaped form, such as the excavator shovel tooth or the plow of the cultivator. Non-uniformity heating on their surfaces can reach 600 °C. Using the power modulation of the remote arc allows to decrease this value to 40-60 °C.

![Figure 1](image_url)

**Figure 1.** Temperature dependence $T_\Sigma$ of the steel base from frequency of its rotation $n$ (rpm) and distribution of average weighted effective thermal power $q_{imp}$ at power modulation of the remote arc: $R = 0.04$ m; $H = 0.002$ m; $T_{\Sigma_{meas}}$ – measured temperature

The results of calculating of the heat flow to the nichromic coating (Ni80%, Cr20%) based on the dependence (1) that provides local penetration of the coating to the transition zone with the base are presented in figure 2 [2]. The analysis of curves shows that with the increasing of the coating thickness of 10 times (from $10^{-4}$ Up to $10^{-3}$ m) the required heat flow to the coating should be increased up to 1-2 multiple of values (at speeds $V = 0.2... 0.8$ m/s). The speed increasing of the plasmatron movement from 0.2 to 0.8 m/s leads to the increasing of the required heat flow to the coating up to 1.5-2.5 multiple of values. Experimental studies have shown that the using of remote arc power modulation on direct polarity diagram allows to increase: strength of the coating connection with the base in 1.15... 1.25 times, microhardness - in 1.1... 1.2 times, resistance to the samples fatigue - up to 1.2 times, wear resistance of coatings-in 1.25... 1.35 times.

**Dual-program power impulse modulation of the remote arc.** The cited studies results show that the power impulse modulation of the plasmatron remote arc can perform two tasks. On the one hand, it is a task of ensuring the uniformity of the temperature field of the base with coating and thermal activation of the base surface before the spraying of the coating that allows to reduce the difference of temperature deformations of the base, creates conditions for uniform distribution of structure and physicomechanical properties of the coating and the base. On the other hand this is a task of discretely distributed local penetration of sprayed coating to the transition zone with the base providing the high coating strength and its connection to the base. The results of the researches show that implementation regimes of these tasks are different. Consequently, performing this complex task of providing the high connection strength of coating with the base at high uniformity of the temperature field of the surface base requires simultaneous realization of the impulse modulation modes of the remote arc on two pro-
grams.

Figure 2. The dependence of heat flow to the coating $q_{imp}$ at the power impulse of the remote arc, providing the penetration of the coating to the transition zone with the base, from the speed of the plasmatron movement $V$ (a) and from the thickness of the coating $h$ (b).

These programs must simultaneously accomplish different durations, periods and amplitudes of power impulse of the remote arc, specifying dimensions, density of distribution on the surface of the local thermal impact zones and its intensity (Fig. 3). The first program is selected according to the condition of providing thermal activation and uniform temperature field of the part surface (Fig. 3, b). It forms impulses $N_a$ with modulation parameters: frequency-100... 2000 Hz, amplitude of power pulses – 100... 700 W, duration of power pulses – 0.05... 1.5 Ms.

The second program is selected under the condition of a given and evenly distributed coating durability on the surface and the connection of the coating with the base by penetration of the local zones of coating to the transition zone of "coating-base" (Fig. 3, c). This program forms the impulses $N_{ml}$ with the modulation parameters: frequency-10... 100 Hz, amplitude of power pulses – 1... 20 kw, power pulses duration – 2... 50 ms.

The programs are implemented together in such a way that total power of the remote arc $N$ (Fig. 3, d) includes the amount of its carrying power $N_a$ with a combination of pulses $N_a$ and $N_{ml}$, and along with this on the temporary sections of simultaneous overlapping of these impulses the amplitude of power impulses equal to the greater of them is assigned.

An example of dual-program implementation of the remote arc modulation of plasmatron in the process of plasma spraying is a process with the following mode parameters. Sand blasted cylindrical sample with diameter of 40 mm from steel 45 (analogue USA steel 1045) was sprayed by self-fluxing powder based on nickel and chromium (Ni 76.4%, Cr 13%, Fe 4%, B 2.8%, C 0.6%) at the spraying distance of 50 mm. The sample was rotated at the frequency of 14 rpm. Plasma-forming gas (air) with a flow rate of 0.6 · 10^{-3} m^3/s was supplied into the plasmatron “ЭДП-104”, then the arc of indirect action with average current of 50 A and average voltage of 100 V, and the bearing arc of direct action between the cathode of the plasmatron and the piece with average current of 5... 10 A and average voltage of 8... 16th V were burned up. It was started the current modulation of the direct action arc in the first program for the surface thermal activation and providing the uniform temperature field in it with parameters: duration of the current pulses – 0.4... 0.5 ms, amplitude of current pulses – 30... 18 A (amplitude of power pulses – 0.5... 0.2 kW), frequency of modulation varied from 1000 Hz on the first coils to 100 Hz on the following ones.

The formed plasma jet was given the sprayed powder with transporting gas (propane) flow rate of 0.05 · 10^{-3} M^3/s, and it was started the supplying the plasmatron along the sample axis, equal to 3 mm at one revolution for coating with layers of thickness 0.35... 0.4 mm each. At the same time, the direct
action arc current modulation in the second program was started to ensure the uniform distribution of the local penetration zones of the coating layers. Parameters of the direct arc current modulation

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure3.png}
\caption{Schematic image of dual-program of the remote arc pulse modulation of the plasmatron: $t$ - time, $N$ – bearing power of the arc; $N_a, N_{ml}, N_{\Sigma}$ – amplitude of the power arc in the first, second program}
\end{figure}
and dual-program modulation accordingly

in the first layer of coating were chosen equal: frequency of modulation of the discharge current - 25... 30 Hz, pulse duration 5... 15 ms, the amplitude of current pulses – 35... 45 A (amplitude of power pulses ~ 2... 3 kW). For the next layers the parameters of current modulation were chosen equal: frequency of modulation of the discharge current-10... 25 Hz, pulse duration 15... 35 ms, amplitude of current pulses – 70... 80 a (amplitude of power pulses ~ 4.5... 6.5 kW).

The test results showed that dual-program modulation in comparison with modulation in the first program at the comparable temperature differential of ~ 5-10 °C noticeably increases the strength of the coating connection with the base to 30-50 MPa. In comparison with the second modulation program dual-program modulation allows slightly to increase the strength of the connection up to 10-15 MPa and to reduce the base temperatures differential to 30-50 °C.

Therefore, the usage of the plasmatron remote arc dual-program modulation allows increasing the flexibility of the spraying process control and as a result providing high strength properties of the coating at high performance of the coating process.

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