Features of thermal processes of plasma deposition and hardening of coatings with external modulation parameters of the arc

A M Kadyrmetov¹, S N Sharifullin², A F Maltsev¹
¹ Voronezh State Forestry academy, 394613, st. Timiryazev, house 8, Voronezh, Russia
² Kazan Federal University, 42000818, Kremlyovskaya str., house 18, Kazan, Russia

E-mail: Saidchist@mail.ru

Abstract. In the work on the basis of mathematical modeling analysis of processes of plasma deposition of coatings with modulation of the electrical parameters of the extension arc. The effect of modulation on the temperature field in the system "coating-basis" on a local scale, proportionate to the diameter of the spot attachment of the arc to the surface, and at the macro-level of evaporation surface. It justifies the preconditions of the improvement of plasma deposition and hardening coatings.

1. Introduction

Current status of plasma technologies of coating and surface hardening shows that the traditional ways of their development on the basis of modifications of stationary processes have reached the limits of a marked improvement in their effectiveness. Analysis of ways to improve plasma deposition and hardening coatings shows that effective improvement is possible by using the methods of dynamic modification of parameters and, in particular, by modulating the electrical parameters of the external arc (straight arc) [1, 2].

The process of plasma spraying and hardening coatings (Pnip) through the use of dynamic effects in the modulation of the electrical parameters of the plasma torch is one of the promising and, however, poorly understood directions. The object of the theoretical analysis Pnip when the modulation of the electrical parameters of the plasma torch remote arc was thermal and physico-mechanical processes in the system "plasma jet and remote arc – coating – substrate". The task was solved by development of mathematical models [3-5] and subsequent simulation of the above objects of study in the modulation of the electrical parameters of the remote arc plasma torch.

The effect of modulation of electrical parameters on temperature field evaporation surface has two space-time dimensions. In aspect local impact on the coating to improve the bonding strength of the coating to the substrate is necessary to provide a discretely distributed local zones of melting of the surface to the transition zone of the "coating-substrate". This is true in particular for coating under dynamic loads [6, 7]. In the aspect of scale of all surfaces is necessary to minimize variation of temperatures on the profile of the substrate surface and the uniformity of its temperature field.

To develop process recommendations in the processes of plasma deposition and hardening coatings requires knowledge of regularities and links between technological factors in the production of coatings in the mode of modulation of external parameters of the arc and thermal criteria of quality of
coatings, determining the level of residual stresses in coatings and their mechanical and tribological properties.

To perform this task have been developed mathematical models of thermal processes describing the processing system of the process of applying and hardening coatings in the modulation mode of the external parameters of the arc.

2. Methods of Research

Methodological basis of theoretical research formed the scientific basis of the theory of thermal welding processes, methods of computational mathematics (finite difference method), modern graphics and computing systems to computers.

3. Mathematical model of thermal processes in the system "coating-basis"

Physical processes in the coating during modulation of the power transferred arc plasma torch with \( \Delta N_p \) amplitude and time of impulse \( \tau \), consist in fusing the coating to the transition zone to the substrate, and the formation of physical contact at time \( t_c \), and the chemical interaction of the coating with the base point in the local zone of direct binding of the arc to the base (coating). Across the surface taking into account the influence of speed \( V \) and feed \( S \) of the plasma torch formed certain distribution density of the discrete zones of melting and of thermal effect on the base and the coating, causing the uniformity of the temperature field base and to increase the physico-mechanical and tribotechnical characteristics of coatings. To estimate the thermal efficiency of the modulation of the electrical parameters during plasma spraying of coatings was constructed mathematical model of the temperature field \( T \) of the system "coating-substrate", which is represented as the sum of the total field away from the source \( T_\Sigma \), local field near \( T_r \) and the initial temperature \( T_0 \) [2, 8]:

\[
T = T_\Sigma + T_r + T_0. \tag{1}
\]

To solve the problem, following assumptions were:

1. The power of the heat source is constant during the pulse (\( N_{imp} = \text{const} \), \( q_{imp} = \text{const} \)).
2. The heat source is concentrated in the elementary point; the error estimation of the temperature from this to a depth equal to the thickness of the coating, can be considered.
3. The heat source is uniformly and rectilinearly moves product at a constant speed (\( V = \text{const} \)).
4. The distribution of heat in the body occurs according to the law of heat conduction Fourier.
5. The boundary of the body is impermeable to heat transfer from the body.
6. The coefficients of the thermophysical properties of the base metal (coefficient of thermal conductivity and volumetric heat capacity) do not depend on temperature.
7. Phase and structural transformations of the metal coating occur without the allocation and absorption of heat.
8. Initial and boundary conditions: \( q \left|_{z \geq 0} = q \right. \left. \frac{\partial T}{\partial z} \right|_{z=0} = 0 \), \( T \left|_{z= \infty} = 0 \right. \).

Then the total field away from the source \( T_\Sigma \) will be installed Rikaline N. N. [9], and describe the limiting state of heat conduction in semi-infinite body heat without moving relative to the heat source on the surface in the direction of the \( 0X \) axis with constant speed \( V \):

\[
T_\Sigma (R, x, \infty) = \frac{q}{2\pi \cdot \lambda \cdot R} \cdot e^{-\frac{V_x}{2a} - \frac{VR}{2a}}, \tag{2}
\]

where \( R \) is the radius-vector from the heat source, m; \( x \), \( y \) – coordinates of the surface of the body, m; \( z \) is the coordinate directed into the body perpendicular to its surface, m; \( V \) – velocity of the heat source, m/s; \( a \) – thermal diffusivity, m\(^2\)/sec; \( \lambda \) – thermal conductivity, W/(m·deg).

When \( x = 0 \) and \( y = 0 \) we have \( R = z \) is the depth of the foundations of the body.

To determine the heat flux to the coating, necessary for its local penetration, and maximum temperature \( T_{\text{max}} \) equal to or greater than the melting temperature of the coating material, the expression (1) has the form:
\[ q_{imp} = \frac{4.25 \cdot V \cdot \rho_m \cdot c_m \cdot \varepsilon^2 \cdot T_{max}}{\xi \cdot \phi(\rho, \tau)}, \]  

where \( V \) – speed of movement of plasma generator, m/s; \( \rho_m \) – the density of coating material, kg/m³; \( c_m \) is specific heat of the coating material, J/(kg°C); \( \varepsilon \) – factor distribution of the heat source:

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

The total power transferred arc \( N_h (W) \) pulse with modulation, ensuring the penetration of the coating at a depth \( h \) (m) to the transition zone to the substrate, was estimated using the expression

\[ N_h = 4.25 \cdot V \cdot c_v \cdot h^2 \cdot T_{as}/\varepsilon, \]

where \( V \) – speed of movement of the spot binding the straight arc surface, m/s; \( c_v \) – volumetric heat capacity of the coating material, J/(kg°C); \( T_{as} \) – melting point material coating, °C; \( r_0 \) is the radius of the spot of the direct binding of arc to the coverage, m.

For cylindrical bodies, sprayed on the helix, the common box away from the heat source \( \Sigma \) expression was determined on the basis of theoretical provisions [10]:

\[ T_{\Sigma}(r, z, \theta, t) = \frac{q_n}{R^2 \cdot C_\gamma} \cdot \frac{1}{\sqrt{\pi}} \cdot \sum_{n=1}^{\infty} \frac{\phi(\rho, \tau_n)}{\sqrt{\tau_n}} \cdot \exp \left[ -\frac{\varepsilon^2 \cdot n^2}{4 \cdot \tau_n} \right], \]

where \( \tau_n = \frac{2\pi \cdot a}{R \cdot V_n} \cdot n \); \( \xi = \frac{H}{R}; q_n = \frac{q}{V_n}; \tau_n \) is the dimensionless complex which characterizes the time; \( \xi \) is the dimensionless complex, which characterizes the spraying step; \( \theta \) is the angular coordinate, rad.; \( q \) – thermal power of the plasma torch, W; \( q_n \) – linear energy, J/m; \( R \) – radius of cylinder, m; \( \phi(\rho, \tau) \) – the function characterizing the process of propagation of heat along the radius of the cylinder; \( n \) – number of turns; \( N = 1, 2, 3 \), etc.; \( V_z, V_\theta \), respectively, the axial and circumferential speed of the heat source, m/s; \( C_\gamma \) – volumetric heat capacity, J/(m³°C); \( H \) – pitch of the, m.

The maximum temperature \( T_{max} \) was determined from the dependence:

\[ T_{max} = \frac{2 \cdot \varepsilon \cdot q}{\pi \cdot e \cdot V \cdot C_\gamma \cdot r_s^2}, \]

where \( r_s \) is the local radius-vector pointing from spot spraying the body parts with coating, m; \( e \) – factor distribution of the heat source.

The density of the thermal noroxaq in the case of modulation of the parameters of the plasma torch is equal to

\[ q = q_0 + q_{imp}, \]

where \( q_0 \) – the load capacity of indirect and remote arc; \( q_{imp} \) – weighted average effective thermal power of the arc remote from the modulating pulses.

Weighted average effective heat output of the modulating pulses is determined by the formula:

\[ q_{imp} = \frac{\Delta q_{imp} \cdot \tau_{imp} \cdot v_{imp}}{\varepsilon}, \]

where \( \Delta q_{imp} \) – amplitude of power pulses; \( \tau_{imp} \) – pulse duration; \( v_{imp} \) – pulse repetition rate.

To solve the heat problem on the estimation of the pulsed power arc \( N_{imp} \) remote from the penetration depth of \( h + \Delta h \) and the speed of the torch \( V \), and the dependence of the number of local penetration zones of the \( n_p \), the processing step \( H \), the pulse width \( t_{imp} \) and the modulation frequency \( v_m \) from the above specified parameters were made given the following options:

- coating thickness \( h \) in the range of 0.1-1 mm and \( \Delta h \) of the transition zone in the range (0.05 ... 0.1)\( h \);
- specific heat capacity \( cm \) and density \( \rho \) of the material of the coating;
- the size of the local penetration of the transition zone of the coating to the Sml basis;
- the area of the base surface \( S_b \).
– the speed of motion \( V \) of the plasma torch;
– duty cycle \( k \) \((k>1)\);
– the proportional limit of the material covering \( \sigma_{lp} \);
– operational stress \( \sigma_e \).

4. Results and discussion

On the basis of decisions (2) for semi-infinite bodies and (5) to the cylindrical body using a method of reflection and superposition (superposition) of the thermal waves, but also taking into account processes of heat and equalization of the medium-integral increase of body temperature were obtained for solutions of the relevant bodies, such as, for example, the tooth of the excavator and the crankshaft. A mathematical model of the temperature field of the system "coating-substrate" is implemented numerically.

In the aspect of the scale of the entire surface of the control parameters external modulation allows the arc to minimize variation of temperatures on the profile of the substrate surface and the uniformity of its temperature field. This is confirmed by the results of calculations for cylindrical parts when plated on the helix (Fig. 1). From the graph of dependence of temperature basis \( T_e \) from the distribution of the average amplitude of the power \( q_{imp} \) and the rotational speed \( n \) can be seen that the temperature spread in the heating output of the pulses is from 2 to 5% of the average. The traditional use of preliminary heating with the plasma torch without longitudinal feed along the cylindrical temperature spread is 10 to 20 percent of the average wage or more, which is 80 – 180 °C more than by using external modulation of the arc. The decrease of the temperature spread on the surface of the part reduces the difference of temperature deformations, creates conditions for a uniform distribution of structure and physico-mechanical properties of coatings and basis. The results of calculations for example the crankshaft of the engine KAMAZ-740 showed that the difference in surface temperature of the sputtering is not more than 2...5 °C is provided by adjusting the weighted average effective heat capacity \( q_{imp} \) by its reduction on the first three threads in the range from 165 to 10 watts for the connecting rod journals and in the range from 370 to 160 watts for indigenous journals.

![Graph showing temperature basis and distribution of weighted average effective heat capacity](image-url)

**Figure 1.** The dependence of the temperature \( T_e \) basis of the frequency of rotation \( n \) and the distribution of the weighted average effective heat capacity \( q_{imp} \) if modulation power extension arc: \( R = 0.04 \text{ m}; L = 0.002 \text{ m} \).

The modulation power extension arc by sputtering on the inner surface of the small-size also helps to ensure the uniformity of the temperature field evaporation surface. Even more relevant to use the power modulation of the extension of the arc during the deposition profile on the surface of parts.
subjected to high wear stresses, such as working bodies tillage, forestry and road construction machinery. In particular, it refers to the wedge-shaped parts such as bucket tooth of excavator, plough, cultivator. On their surfaces the uneven heating may reach 600 °C. The modulation power extension arc allows to reduce this value to 10 to 20 °C.

The results of the calculation of the heat flow to the nichrome coating (H80X20), similar in composition to the material self-fluxing Nickel-base PG-CP4, which provides the penetration of the coating to the depth of the transition zone with the base presented in Fig. 2, 3 [11]. Analysis of the curves shows that with increasing thickness of the coating is 10 times (from $10^{-4}$ to $10^{-3}$ m), the required heat flux to the surface must be increased by 1 – 2 orders of magnitude (in the velocity $V = 0.2...0.8$ m/s). Increase the speed of the plasma torch from 0.2 to 0.8 m/s increases the required heat flux to the surface of $1.5 – 2.5$.

![Figure 2](image1.png)

**Figure 2.** The dependence of the heat flux to the surface $q_{imp}$ when the pulse power remote arc, ensuring the penetration of the coating to the transition zone with the base, on the speed of the torch $V$

![Figure 3](image2.png)

**Figure 3.** The dependence of the heat flux to the surface $q_{imp}$ when the pulse power remote arc, ensuring the penetration of the coating to the transition zone to the substrate, the thickness of the coating $h$

It is known that the formation of a strong connection of the melt with the solid phase is only possible as a result of physical contact and chemical interaction between them. This can be achieved if
the contact time between the phases is not less than the sum of the delay time of diffusion transitions and development processes heterodiffusion before the formation of supersaturated solid solutions. It is known that the diffusion processes during solidification of metals are three stages with characteristic time constants of $10^{-12} – 10^{-10}$, $10^{-8} – 10^{-5}$ and $(0.5 – 1.5)10^2$ s, corresponding to oscillation periods of atoms and translational switch groups of atoms, the oscillation periods of the clusters and displacement of layers of clusters. This suggests that, at least temporarily condition the formation of a firm connection is ensured when the pulse over 10 ms. If enough are the first two stages of crystallization, this time should be more than 10 iss, which requires confirmation in additional studies.

Consider the results of the calculation for material Н80Х20 and the selected source of data:

- $c_m = 750$ j/(kg•K);
- $\rho_m = 8400$ kg/m$^3$;
- $a = 1.65\times10^{-5}$ m$^2$/s;
- $\sigma_e = 300$ MPa;
- $T_{max} = T_{mel} = 1400$ °C;
- $h = 0.1-1$ mm;
- $\Delta h = (0.03 0.05...)$ mm;
- $V = 0.001-0.8$ m/s;
- $S_b = 0.0168$ m$^2$;
- $S_{ml} = 1.3\times(10^{-8}...10^{-6})$ m$^2$;
- $k = 4 – 6$. Heat flux to the surface, ensuring penetration of the coating to the transition zone to the substrate, when such data can be evaluated according to the graphs in Fig. 2, 3.

The use of power modulation of the plasma torch remote arc should ensure the penetration of the coating to the depth of the transition zone with the base $h + \Delta h$ at evenly distributed plots, each $S_f$ during the movement of the plasma torch at a speed $V$ (Fig. 4, 5). The cross section of each plot is close to a semicircle. The total number of zones with a penetration coating must be selected on the basis of the factor of safety that exceeds the operating load surface.

**Figure 4.** The transverse cross section of the molten zone of the coating formed from the pulse power transferred arc: $r_{ml}$ – the radius of the molten zone surface; $h$ is the coating thickness; $\Delta h$ is the thickness of the transition zone; $b_{ml}$ – width of the molten transition zone

You want to find the dependence of the pulsed power arc $N_{imp}$ remote from the penetration depth of $h + \Delta h$ and the speed of the torch $V$, and the dependence of the number of local penetration zones is $N$, the processing step $H$, the pulse width $t_{imp}$ and the modulation frequency $v_m$ from the above specified parameters.

**Figure 5.** Scan a cylindrical surface and arrangement of the fused areas of the coating: $D$, $L$ – diameter and length of cylinder, respectively; $S_b$ is the area of the cylindrical surface; $S_{ml}$, $l_{ml}$, $b_{ml}$ – area, length and width of the transition zone of the molten coating to the substrate, respectively; $H$ is the step helix machining

The number of local zones of melting is in the range from 3432390 pieces for the coating thickness is 0.0001 m ($S_{ml} = 1.34\times10^{-8}$ m$^2$; $b_{ml} = 6.4\times10^{-5}$ m; $l_{ml} = 2H$) to 34324 pieces for a coating thickness of 0.001 m ($S_{ml} = 1.34\times10^{-6}$ m$^2$; $b_{ml} = 6.4\times10^{-6}$ m; $l_{ml} = 2H$).
\[ b_{\text{ad}} = 0.00064 \text{ m}; \quad l_{\text{ad}} = 0.0021 \text{ m}; \quad H = 3.5 \text{ mm}. \] The pulse duration is the interval from 75 iss to 37.5 ms (modulation frequency of \( v_m = 20...10000 \text{ Hz} \)).

Experimental studies have shown that modulation of the extension of the arc straight polarity allows to obtain coatings with high physical-mechanical and tribotechnical properties. In comparison with the coating without direct modulation of the arc: the bond strength of the coating to the substrate is increased to 1.15...1.25 times, microhardness is 1.1...1.2 times, fatigue resistance of the samples to 1.2 times the wear resistance of coatings – 1.25...1.35 times. The porosity of coatings decreases 1.2...1.3 times. Improving the basic physical and mechanical properties of the coatings allows the use of the developed technology for components operating at alternating and cyclic loading.

4. Conclusions

The mathematical model of thermal processes in plasma spraying of coatings with pulse modulation external arc plasmatron allows to calculate the parameters of power amplitude and pulse width and frequency modulation, providing local penetration of the coating to the transition zone to the substrate, and a uniform temperature field. The dependence of the power of the arc remote from the thickness of the coating identical to that for the case of stationary heat source. Possible calculation error can be eliminated by conducting experiments clarifying.

The results of calculations allow to determine the optimal spacing of the heat action, which provides higher strength characteristics of coatings in comparison with conventional plasma spraying.

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