

## Mathematical modeling of plasma deposition and hardening of coatings-switched electrical parameters

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**Abstract.** This paper presents the results of simulation of plasma deposition and hardening of coatings in modulating the electrical parameters. Mathematical models are based on physical models of gas-dynamic mechanisms more dynamic and thermal processes of the plasma jet. As an example the modeling of dynamic processes of heterogeneous plasma jet, modulated current pulses indirect arc plasma torch.

### 1. Introduction.

One of the most progressive and effective lines of creating parts with desired properties on their working surfaces is a protective coating of gas-thermal methods. In this group, one of the most effective and universal method is plasma spraying. Existing ways of improving the plasma spraying, aimed at improving the efficiency of stationary coating, almost exhausted, and limited to an insufficient level of physical-mechanical and tribological properties of coatings subjected to high dynamic alternating and shock loads performance. Some work is devoted to improving the plasma deposition methods dynamizing processes using acoustic impact on the plasma jet (SSI "Institute of Heat and Mass Transfer" NASB), and pulsed arc power bypass (SSTU, St. Petersburg, MSTU. NE Bauman). However, questions remained unstudied theoretical description of processes at the modulation parameters of the plasma spraying and methodical study of optimization.

Based on the study of general questions of plasma spraying process can be concluded that improving the efficiency of plasma spray technology is advantageously carried out by the improvement, development and universalization of both the technological operation spray coating and subsequent processing steps of hardening or combining with them [1].

Improvement of the process step of spraying may be achieved by modulating the parameters of the plasma torch, by adding additives to the plasma gas (the plasma for the air - by the addition of carbohydrate-gen-containing gas), gas dynamic processes, and by combining these methods using [2, 3].

Modulation of the electrical parameters of the plasma spraying (current arc plasma torch) is technological method to simply and effectively regulate the power and energy of the arc by increasing or decreasing the pulse arc power at a certain frequency. It allows you to: generate a plasma jet at low intensity shock waves and intense acoustic waves; increase the drag coefficient of the spray particles and heat them to two or more times and thus enhance the energy parameters of the spray particles (increase of the speed and temperature of 30 ... 50%) [2-8]. This ensures increasing the density and strength of the coating.

The technological method of adding to the hydrocarbon-containing gas plasma air can increase the enthalpy and the thermal conductivity of the plasma jet to 2 times, create a neutral and a reducing atmosphere; increase the thermal efficiency of the plasma torch; increase the temperature of the



plasma jet (from 5300 °K air to 6200 °K for propane in air) and the speed of the plasma jet and the sprayed particles by 10 ... 30% [3, 9].

For the development of technical advice in the process of plasma deposition and hardening of coatings requires knowledge of patterns and relationships between technological factors in the production of coatings in the mode of modulation parameters and gas-dynamic and thermal coatings quality criteria that determine the level of residual stresses in the coatings, their strength and tribological characteristics.

To accomplish this task have been developed mathematical models describing the technological system during application and hardening coatings mode modulation parameters.

## 2. Research methods.

Methodological basis of theoretical studies have made the scientific basis of mechanical engineering, the theory of gas dynamics in terms of jet streams, traveling wave velocity and entropy waves temperature, the theory of thermal welding processes, methods of computational mathematics (finite difference method and discrete components), advanced graphics and computer systems for the computer.

## 3. Results.

Technological use of dormant plasma deposition of hardening coatings modulates electrical parameters based on physical models of gas-dynamic mechanisms more dynamic and thermal properties, which are caused by the conversion of electrical energy pulse current indirect or remote arc modulation thermal and gas-dynamic energy of the arc and the space around it. Physical processes in the plasma jet in the modulation of indirect arc plasma generator with a frequency modulation  $\nu_m$  duration  $\tau_m$ , amplitude  $\Delta N$  and steep power  $dN/dt$  pulses is to generate in the plasma jet of entropy heat waves with the amplitude of the temperature  $\Delta T_p$  and shock waves with Mach number  $M$ , appropriate strong or weak shock waves [10]. The result of the impact of these waves on the plasma jet is heterogeneous: increased turbulence in the plasma jet, leading to an increase in the uniformity of its cross-profile  $A$  range of a temperature  $L_T$  and enthalpy  $L_{\Delta H}$ ; increasing the drag coefficient  $C_D$  and particle heat transfer them  $\alpha$  by the plasma jet; increasing the speed  $V_p$  particles and their heating rate  $dT_p/dt$ . Such an increase in the energy state of the particles provides improvement of physical contact of the particles with the substrate and connected to it by increasing the pressure and the pulse pressure of the particles to the substrate upon impact, which results in a decrease of porosity  $P$  and increase strength coating performance (adhesion and cohesion  $\sigma_k$   $\sigma_a$ ). Physical processes in the coating in the modulation of the direct arc torch with an amplitude  $\Delta N_d$  and pulse time  $\tau_m$  consist of fusion of the coating to the transition zone to the substrate and the formation of physical contact for the time  $t_c$  and chemical interaction covering the substrate in point local zones bind direct arc to the base (coating). On the scale of the entire surface with the influence of the speed  $V$  and feed  $S$  torch formed certain density distribution of discrete zones of penetration and thermal effect on the substrate and the coating that contribute to the uniformity of the temperature field bases and improving mechanical and tribological characteristics of the coating.

Formation conditions and the quality of the coating are determined by the energy impact on the formed coating through three channels: from the sprayed particles (parameters speed  $V_p$ , the temperature of  $T_p$  and heat flow  $q_p$ ), gas phase plasma jet (the parameters of the speed  $V_g$ , the temperature  $T_g$ , heat flows heat  $q_g$  and cooling  $q_c$ ) and thermal and electromechanical effects on the sprayed surface and coating (direct arc power parameter  $N_p$  and its amplitude, pressure roller and its amplitude  $\Delta P$ , heat flows from the thermal  $q_t$  and electromechanical  $q_e$  effects, thermal conductivity  $\lambda$  and heat capacity  $c_p$  materials, radii shaft  $R_{sh}$  and run-roller  $R_r$ , shaft speed  $n_{sh}$  and pitch of turns spraying  $H$ ). The model shows that for the process to ensure the quality of decisive importance is the effect of two physical components of the plasma process: the energy state of the particles of the coating material and the thermodynamic state of the "coating-base." Therefore, the complexity of the physical processes described in the "indirect and direct arc - plasma jet - Floor - base" in the

modulation mode, the electrical parameters of the plasma torch arcs led to the need to provide the system of partial models. Their study allows us to solve the problem of getting better quality coatings in a complex mathematical models that include a description of the processes with the modulation parameters: gas-dynamic, temperature field distribution of the "coating - substrate" with regard to the cooling surface deposition, thermal and electro-coating treatment.

Here we consider one of the private mathematical models developed for the dynamic processes of heterogeneous plasma jet, modulated current pulses indirect arc plasma torch. It includes a stationary-phase empirical description of the plasma jet, an analytical description of the stationary distribution in the jet traveling wave velocity and temperature and entropy waves the description of the behavior of spray particles in modulating plasma jet.

On the basis of the equations of motion and continuity of the gas phase distribution of the plasma jet traveling wave velocity jet axis  $x$  stands for a solution:

$$x = \left( \frac{\chi+1}{2} \cdot V_{\text{var}} + V_{\text{fix}} + c_{\text{fix}} \right) \cdot t + f(V_g), \quad (1)$$

where the gas velocity is  $V_g = V_{\text{var}} + V_{\text{fix}}$ ;  $V_{\text{var}}$ ,  $V_{\text{fix}}$  - respectively variable and fixed components of the velocity of the plasma torch to cut, m/s;  $c_{\text{fix}}$  - the speed of sound in the undisturbed environment at  $V_g = V_{\text{fix}}$ , m/s;  $t$  - time, s;  $\chi$  - polytropic index. Function speed  $f(V_g)$  determined from the boundary conditions change the speed at the nozzle exit of the plasma torch generated triangular wave power indirect arc of dependencies for the first and second half pulses, respectively:

$$V_{g0} = V_{\text{fix}} + \frac{2V_a}{\tau_{\text{mom}}} \cdot \tau \quad \text{at } n \cdot \tau_{\text{per}} < \tau < \frac{\tau_{\text{mom}}}{2} + n \cdot \tau_{\text{per}},$$

$$V_{g0} = V_{\text{fix}} - \frac{2V_a}{\tau_{\text{mom}}} \cdot \tau + 2V_a \quad \text{at } n \cdot \tau_{\text{per}} + \frac{\tau_{\text{mom}}}{2} < \tau < \tau_{\text{mom}} + n \cdot \tau_{\text{per}}, \quad (2)$$

where  $n = 0, 1, 2, 3, \dots$ ;  $V_{g0}$ ,  $V_a$  - respectively, the gas velocity and amplitude of its fluctuations at the nozzle exit of the plasma torch, m/s;  $\tau_{\text{mom}}$ ,  $\tau_n$  - respectively, the pulse duration and the period of its pulsations, p.

The initial conditions corresponding to the distribution of the parameters of the plasma jet along its  $x$ -axis describes the dependence:

$$V_m(x) = V_{\text{fix}} \cdot \sqrt{\pi \cdot \left[ \phi(x) + (1 - \phi(x)) \cdot \frac{T_{\text{norm}} - 300}{T_{\text{fix}} - 300} \right]}, \quad T_m(x) = \phi(x) \cdot T_{\text{fix}} + (1 - \phi(x)) \cdot T_{\text{norm}},$$

$$\rho_m(x) = \frac{\rho_{\text{fix}}}{\phi(x) + (1 - \phi(x)) \cdot \frac{T_{\text{norm}} - 300}{T_{\text{fix}} - 300}}, \quad c_m(x) = \sqrt{\chi \cdot P / \rho_m(x)} \quad (3)$$

where for the initial portion of the plasma jet  $\phi = 1$ ,  $\pi = 1$ ; for the transition -  $\phi \sim 0,5$ ,  $\pi \sim 0,6$ ; for the main -  $\phi \sim 0,1$ ,  $\pi \sim 0,1$ ;  $V_m(x)$  - velocity at the axis of the plasma jet in m/s;  $T_{\text{norm}}$  - normal temperature,  $T_{\text{norm}} = 300$  K;  $T_{\text{norm}}(x)$  - the temperature on the axis of the plasma jet, K;  $\rho_m(x)$  - the gas density at the jet axis, kg/m<sup>3</sup>;  $c_m(x)$  - the sound velocity on the axis of the plasma jet in m/s;  $P$  - pressure, Pa.

For the initial portion of the plasma jet at intervals of time corresponding to the first half of the pulse arc power, based on the expressions (1) and (2) the dependence of the variable speed of the gas phase in the form:

$$V_{\text{var}}(x, t) = \frac{V_a \cdot t}{\tau_{\text{mom}}} - \frac{c_{\text{fix}} + V_{\text{fix}}}{\gamma + 1} + \sqrt{\left( \frac{V_a \cdot t}{\tau_{\text{mom}}} - \frac{c_{\text{fix}} + V_{\text{fix}}}{\gamma + 1} \right)^2 - \frac{4 \cdot V_a}{\tau_{\text{mom}} \cdot (\gamma + 1)} \cdot \left[ x - (c_{\text{fix}} + V_{\text{fix}}) \cdot t \right]},$$

and for times corresponding to the second half of the pulse, - in the form:

$$V_{\text{var}}(x, t) = -\frac{V_a}{\tau_{\text{mom}}} \cdot t - \frac{c_{\text{fix}} + V_{\text{fix}}}{\gamma + 1} + V_a + \left\{ \left( -\frac{V_a}{\tau_{\text{mom}}} \cdot t - \frac{c_{0m} + V_{0m}}{\gamma + 1} + v_a \right)^2 + \frac{4 \cdot V_a}{\tau_{\text{mom}} \cdot (\gamma + 1)} \cdot \left[ x - (c_{\text{fix}} + V_{\text{fix}}) \cdot (t - \tau_{\text{mom}}) \right] \right\}^{\frac{1}{2}}.$$

Entropy waves carried along with the flow, so the general solution of the temperature distribution in the longitudinal coordinate stream of  $x$  and time  $t$  is given by:

$$T(x, t) = T \left( 0, t - \frac{x}{V_{\text{mom}}} \right).$$

Based on the boundary conditions corresponding to the change in temperature at the nozzle exit of the plasma torch in the form of a triangular wave generated by the pulse power of indirect arc:

$$\begin{aligned} T_{g0} &= T_{\text{mom}} + \frac{2T_a}{\tau_{\text{mom}}} \tau \quad \text{at } n \cdot \tau_{\text{per}} < \tau < \frac{\tau_{\text{mom}}}{2} + n \cdot \tau_{\text{per}}, \\ T_{g0} &= T_{\text{fix}} - \frac{2T_a}{\tau_{\text{mom}}} \cdot \tau + 2T_a \quad \text{at } n \cdot \tau_{\text{per}} + \frac{\tau_{\text{mom}}}{2} < \tau < \tau_{\text{mom}} + n \cdot \tau_{\text{per}}, \\ T_{g0} &= T_{\text{fix}} \quad \text{at } n \cdot \tau_{\text{per}} + \tau_{\text{mom}} < \tau < (n+1) \cdot \tau_{\text{per}} \end{aligned}$$

and initial conditions (3) analytical temperature versus distance  $x$  and time  $t$ , where  $Ta$  - the amplitude of the temperature, K.

In the initial section of the plasma jet for the time corresponding to the first half of the pulse power of the arc, the expression for the temperature of the gas phase is of the form:

$$T_{\text{norm}}(x, t) = T_{\text{fix}} + \frac{2 \cdot T_a}{\tau_{\text{mom}}} \cdot \left( t - \frac{x}{V_{\text{fix}}} \right),$$

for the time corresponding to the second half of the pulse - form:

$$T_{\text{norm}}(x, t) = T_{\text{fix}} + 2 \cdot T_a - \frac{2 \cdot T_a}{\tau_{\text{mom}}} \cdot \left( t - \frac{x}{V_{\text{fix}}} \right).$$

Similar expressions variable speed and temperature of the gas phase are obtained for the transition and main portions of the plasma jet.

Changing the speed and temperature of the particles described by the equations of motion and heat balance in the quasi-stationary approximation, corresponds to what the drag coefficient and the heat transfer particles depend only on the instantaneous values of the hydrodynamic parameters. This is justified by the smallness of the time of establishment of the stationary boundary layer of particles equal to 0.1-10 microseconds, compared to the duration of the modulating pulses of the order of 100-1000 microseconds.

#### 4. Conclusions.

1. It is shown that the description of the process of application and hardening coatings mode modulation parameters is possible on the basis of mathematical models developed on the basis of physical models of gas-dynamic mechanisms more dynamic and thermal parameters of the plasma jet.
2. Consider one particular mathematical models developed for heterogeneous gas-dynamic processes of the plasma jet, modulated current pulses indirect arc plasma torch. A mathematical model of heterogeneous plasma jets is implemented numerically by the Euler 2nd order. Description of pressure fluctuations in the plasma jet simulation model is implemented in a computer program.

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