Improvement of Adhesion Strength of the Sprayed Material

S A Kornilovich, G V Redreev, D A Vorobyov, S V Zakharov
Omsk State Agrarian University named after P. A. Stolypin
644008, Omsk, Institutskaya square st., 1
E-mail: weerwg@mail.ru

Abstract. The effective way of enhancing resistance to deterioration of the parts is the change of surface properties due to coating with the required properties. Since the deposition process takes place at an elevated temperature, it is necessary to ensure the absence of phase and structural transformations in the metal, mixing of materials, changes in the chemical composition of the coating. The use of plasma spraying at the transport management facility showed a sufficiently high quality of the coating. However, the metallographic analysis showed the presence of discontinuities at the interface in the form of pores, oxide film and sections of decarburized steel. In the case of the process of melting–spraying, the overheating areas of the base metal are formed, which leads to disadvantages similar to the deposition process. To ensure the minimal thermal impact on the part, the thermal field calculations are required. For this purpose, the time of local melting of the part by a single-phase plasma jet was calculated. The temperature field of a part in which heat is transferred by thermal conductivity, the solution of the differential equation of thermal conductivity is described. The boundary conditions of three genera are formulated. The first kind is the distribution of temperature on the enclosing surfaces. The second kind – the task on the surface of the part of the heat flux density. The third kind – setting the temperature of the medium, which acts as a plasma jet, washing the surface of the part, and the intensity of heat exchange. The mathematical model of melting of the product is constructed. The formula for calculating the reflow time is derived. The temperature distribution expressions for the molten and solid zones are obtained by the solution of the problem with moving boundaries by the Fourier’s method. On the basis of theoretical calculations it is proposed to increase the strength of the sprayed layer with the base to apply the process of plasma spraying with preliminary local melting by periodic exposure to a single-phase plasma jet.

1. Introduction
Spraying of the material is a productive and relatively simple process that provides a small heating of the part, the possibility of regulating the chemical and phase composition of the coating within a wide range and high wear resistance.

The essence of the material deposition as a coating process is to heat the material, its dispersion, transfer of the material by a plasma jet and impact on the coated surface, deformation of the particles and their fixation on the basis of (the area of the coated surface of the item).

According to the scientific conclusions of academics V.I. Chernoivanov and E.S. Karakozov [1], the main conditions for the formation of high-quality coatings are: the heating of the part should not cause phase or structural transformations in the metal; mixing of the base and coating materials should be minimal; there should be no reactions that cause a change in the chemical composition of the coating compared to the starting material; in the zone of the compound should not develop relaxation processes that can change the structure and phase composition of the metal [2]. These requirements correspond to a method of applying a coating by plasma deposition of a metal layer on the recoverable, as well as manufactured parts [2-3].

The experience of using plasma spraying at a car repairing plant when restoring parts of fixed joints using the nickel-aluminum powder PN85YU15 as a substrate showed a positive quality of coatings. In this case, the coating of the surface of the parts of movable joints without applying a substrate was obtained of poor quality.
A metallographic analysis of the coating state and base metal after plasma spraying of the central factory of «Transmash» laboratories showed the following: nothing was found at the interface that could lead to the formation of an oxide film, as well as areas of the decarburized steel to pure ferrite; the microstructure of the sprayed layer is a heterogeneous-layered structure with the participation of a spherical shape, there are areas of austenitic-martensitic and bainitic-austenitic structures. Martensite has been significantly increased. The areas after the plasma deposition of the layer had different hardness from HRC 35-40 to HRC 50-60 (measured by microhardness). The adhesion strength of the coating did not exceed 1...6 daN/mm², which is an order of magnitude lower than the strength of the base metal. After subsequent melting, the strength of the coating layer is much higher – 30...40 daN/mm². However, the zone of thermal influence increases, at a depth up to 2.5 mm, the overheating areas of the base metal are formed. There is a process similar to the process of surfacing with its inherent disadvantages.

In cases of using wire instead of a powder made of carbon steel without a substrate of nickel-aluminum alloy, a significant disadvantage of plasma spraying is the low adhesion strength of the coating to the substrate. Increasing the adhesion strength of the coating layer with the base is possible when spraying the material on the pre-melted surface of the part [4].

Pre-melting is carried out periodically in the order of «melting–spraying». Melting is carried out by a plasma jet without feeding the sprayed material. After melting, the supply of the sprayed material is resumed. To simplify the article provisionally called the plasma jet without the sprayed material as the «single-phase», and with the spraying material – the «two-phase». The repeated experiments performed at the Department of Technical Service, Mechanics and Electrical Engineering of Omsk State Agrarian University showed that the depth of the melted layer should be minimal - no more than the thickness of the film held on the surface due to tension forces. Outwardly, such a fusion corresponds to the physical state of «fogging». With an increase in the penetration depth of the liquid metal is blown by a plasma jet to the sides, a crater is formed, in addition, the part is heated unnecessarily, which is incompatible with the essence of the deposition process of the items.

The process of deposition requires a minimum thermal effect on the part, without any noticeable structural changes. The maximum heating of the part should not exceed the high tempering temperature [4-7]. At the same time, the adhesion strength of the sprayed layer increases with increasing temperature on the surface until it melts. The determination of the state prior to the melting point (time t) -x is possible by calculating the thermal field [5-8]. The most General description of the thermal field is the expression of the dependence $t = f(x,y,z,\tau)$ as a differential equation.

2. Results
The calculation of the local melting time of a part by a single-phase plasma jet is made in the following sequence.

2.1. Description of the temperature field of the sprayed part
The description of the temperature field of the part in which heat is transmitted by thermal conductivity can be done by solving the differential equation of thermal conductivity [2]. To simplify the derivation of the equation in the case of a non-standard thermal conductivity process in a stationary homogeneous and isotropic body, it can be assumed that the physical parameters of the body are constant, the deformation of the object under consideration associated with a change in temperature is small and can be neglected, the relative movement of body parts is absent.

To derive the equation, select an elementary parallelepiped with edges $dx$, $dy$, $dz$ in the volume of the heated part, placing it relative to the rectangular coordinate system, and assuming that there is no internal heat source (Figure 1):
Figure 1 – Elementary volume of the heated metal to the solution of the differential equation

The heat flux vector through the elementary parallelepiped is decomposed along the coordinate axes. Considering its component in the direction of the X axis, we denote the elementary amount of heat obtained by the left side of the parallelepiped from the plasma jet in contact with it, by dQx1, and the heat transferred by the adjacent layer by the opposite face is dQX2.

According to Fourier’s law, taking the temperature of the left face equal to $t$, the expression for dQx1 can be written as follows:

$$dQ_{x1} = -\lambda \frac{\partial t}{\partial x} dydz , (1)$$

where $\lambda$ – the thermal conductivity

The change in body temperature in the direction of the x-Axis is indicated as $\frac{\partial t}{\partial x}$, on the segment dx the change in temperature will be equal to $\frac{\partial t}{\partial x} dx$, so the temperature of the opposite right side of the parallelepiped can be represented as a sum

$$t + \frac{\partial t}{\partial x} dx$$

Accordingly, we write the expression for $dQ_{x2}$ as:

$$dQ_{x2} = -\frac{\partial t}{\partial x}(t + \frac{\partial t}{\partial x} dx) dydz$$

or after opening the brackets we will have:

$$dQ_{x2} = -\frac{\partial t}{\partial x} dydz - \frac{\partial^2 t}{\partial x^2} dx dydz$$

(3)

The amount of heat dQx, which went to the heating of the parallelepiped during dt (from the component transmitted in the direction of the x axis), can be obtained by subtracting from the right side of equation (1) the right side of the equation (3):

$$dQ_x = -\frac{\partial t}{\partial x} dydz + \frac{\partial t}{\partial x} dydz + \frac{\partial^2 t}{\partial x^2} dydz dx = \frac{\partial^2 t}{\partial x^2} dydz dx$$

(4)

If we make similar arguments about the other two components of the heat flux vector along the y and Z axes, we can write:

$$dQ_y = \frac{\partial^2 t}{\partial y^2} dxdydz ,$$

$$dQ_z = \frac{\partial^2 t}{\partial z^2} dxdydz ,$$

(5)

(6)

To obtain a complete picture that reflects the qualitative and quantitative characteristics of a particular problem, it is necessary to mathematically set this problem, determined by the conditions of its uniqueness in the form of geometric conditions (shape and size of the part), physical (the value of the coefficients of heat and thermal conductivity), as well as boundary [3]. The composition of the boundary conditions to the heat equation includes time (initial temperature distribution in the volume of the part) and boundary, determining the heat transfer at the boundaries of the part. These conditions
together determine a single state, and in this sense can be called the conditions of uniqueness, and the problem solved with their help - the boundary value problem [2,4].

The initial temperature distribution in the part can be different. For example, at the initial moment of heating or cooling (t = 0) the part has the same temperature throughout its mass:

\[ t(x,y,z) = t_c \]  \hspace{1cm} (7)

In general, the initial temperature distribution in the part is given by the equation \( t = f(x,y,z) \) (at \( t = 0 \)). Boundary conditions can be formulated in one of three ways.

1. The boundary conditions of the first kind are determined by the temperature distribution on the enclosing surfaces as a function of the position of the surface point and time. In conditions of the first kind, the problem of pure heat conduction is considered. This is the only possible mechanism of heat transfer through the wall from one of its boundary surfaces to another.

2. The boundary condition of the second kind consists in setting the heat flux density on the part surface as a function of time and coordinates. These tasks are characteristic of the heat exchange process.

3. The boundary conditions of the third kind consist in setting the temperature of the medium \( T_c \), (plasma jet) washing the surface of the part and the intensity of heat transfer (heat transfer) between this medium and the surface of the part. The process of heat transfer is described by Newton’s – Richman law, according to which the amount of heat given or received by the body from the environment is proportional to the surface area of the body, the temperature difference of the body \( t_b \) and the environment \( t_c \) and the duration of the process:

\[ Q = \alpha(t_c - t_b)F\tau \] \hspace{1cm} (8)

or

\[ Q = \alpha(t_c - t_b)F \] \hspace{1cm} (9)

If we take in equation (8) \( F \) and \( \tau \) equal to one, then \( a = Q/(t_c - t_b) \) represent a value numerically equal to the amount of heat exchanged per unit time unit surface of the part with the medium of the unit temperature difference between them.

In general, the heat transfer coefficient reflects the combined effect of convection and thermal conductivity of the medium, and therefore depends on many factors. It is obvious that the heat flux given by a single surface of the part medium should be equal to the heat flux supplied by the thermal conductivity of the internal volumes of the part to its surface, i.e.

\[ \alpha(t_c - t_b) = -\lambda\frac{\partial t}{\partial n} \text{ or } -(\frac{\partial t}{\partial n})_c = -(\alpha/\lambda)(t_c - t_b), \] \hspace{1cm} (10)

This expression is the most general record of the boundary condition of the third kind [2-3].

2.2. Mathematical model of the sprayed part melting

The mathematical model can be built on the example of melting the product according to the scheme (Figure 2).

Figure 2 – The model of the reflow coating part: \( t_{in} \) – the initial temperature; \( t_{pl} \) – the temperature in the phase boundary (solid and molten); \( t_o \) – the ambient temperature; \( \delta(t) \) - the coordinate of the phase boundary; \( t_{pl} \) – the plasma temperature
Imagine that the item has a sufficiently large thickness, such that the temperature perturbations on one surface will not reach the other surface during the period of time. The body is initially in a solid state at a given temperature \( t_{m} < t_{pb} \). In the simplest case, it can be assumed that, starting from a certain point in time \( t = 0 \), a constant temperature \( t_{m} > t_{pb} \) (a boundary condition of the first kind) is established on the bounded surface and during the period under consideration, which leads to the formation of a melted layer.

The lower boundary of this variable-coordinate layer is the interface (liquid and solid) and maintains a constant temperature \( t_{pb} \). On this surface, the heat of the phase transition is released, equal to the melting heat of the material (for steel \( \sim 272.1 \) kJ/kg). As the phase boundary progresses, the solid zone is heated and melted, but at a sufficient distance \( (x \rightarrow \infty) \) the temperature retains the initial value \( t_{m} \). Obviously, the heat transfer occurs only in the direction of the X-axis. We denote the thermophysical parameters in the molten layer \( \lambda_{p}, C_{p}, \alpha_{p}, \) and in the solid \( \lambda_{m}, C_{m}, \alpha_{m} \). In the simplest case, the density of the molten and solid material will take the same:

\[
\rho_{p} = \rho_{m} = \rho = \text{Const}.
\]

It is required to find the temperature field in the molten and solid \( t_{m}(x, \tau) \) zones, as well as the law of displacement in time of the interface \( \delta(\tau) \) and the velocity of this boundary \((d\tau/d\delta – \text{the melting rate})\).

### 2.3. Mathematical formulation of the problem. Formula derivation for calculating the reflow time

The differential heat equation for different conditions can be written as:

- a) for the molten zone

\[
\frac{\partial \tau_{p}}{\partial \tau} = \alpha_{p} \frac{\partial^{2} \tau_{p}}{\partial x^{2}} \text{ where } 0 < X \leq \delta(\tau); \tau > 0
\]  

(11)

- b) for the solid zone

\[
\frac{\partial \tau_{m}}{\partial \tau} = \alpha_{p} \frac{\partial^{2} \tau_{m}}{\partial x^{2}} \text{ where } \delta(\tau) \leq X \leq \infty; \tau > 0
\]  

(12)

Initial condition: where \( \tau = 0, t(0, 0) = t_{m}, \delta(0) = 0 \).

External boundary conditions: where \( X = 0; \tau > 0; \ t(0, \tau) = t_{0} = \text{Const} \); where \( X \rightarrow \infty; \tau = 0; t \rightarrow \infty, \tau) = t = \text{Const} \).

It is also necessary to formulate conditions on the internal mobile interface. These two conditions. The first condition is the equality of the temperature of the molten and solid zones. The second – the equation of heat flow from the molten and solid zones. To formulate it mathematically, we write the heat balance equation on the phase boundary for the elementary time interval \( dt \). Due to the simultaneity of the problem, the area of the calculated surface can be any. We will calculate on \( 1 \) m\(^2\). The amount of heat coming from the molten zone should be equal to the sum of the heat withdrawn from the phase boundary to the solid zone and the heat of the phase transition absorbed at the boundary:

\[
dQ_{m} = dQ_{s} + dQ_{pb}
\]  

(13)

According to Fourier’s law:

\[
dQ_{m} = \frac{\partial \tau_{p}}{\partial \tau} + \frac{\partial \tau_{m}}{\partial \tau} \text{ and } dQ_{s} = \frac{\partial \tau_{s}}{\partial \tau} \text{ and } dQ_{pb} = \frac{\partial \tau_{pb}}{\partial \tau} \text{ where } \delta(\tau)
\]  

(14)

At this time \( \frac{\partial \tau_{p}}{\partial \tau} + \delta \) and \( \frac{\partial \tau_{m}}{\partial \tau} - \delta \) - the temperature gradient at the interface in the molten and solid zones.

During \( d\tau \), the interface will move by the value of \( d\delta \), so, based on \( 11 \) m\(^3\) of the surface, the volume will melt: \( dV = Ld\delta \), and the amount of heat of the phase transition will be:

\[
dQ_{pb} = H_{pb} \times dV = H_{pb} \times d\tau \times L
\]  

(15)

The equation of the heat balance after transformations at division by \( d\tau \) takes the form at \( x = \delta(\tau) \):

\[
\frac{\partial \tau_{p}}{\partial \tau} + \delta = \frac{\partial \tau_{m}}{\partial \tau} + H \frac{d\delta}{d\tau}
\]  

(16)

Here we introduce the designation \( H = G \cdot L \cdot \rho \). The value \( H \) can be interpreted as the heat of the phase transition unit volume.

\[
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\]
The solution of the problem with moving boundaries by Fourier’s method leads to the temperature distribution expressions:

a) in the molten zone

\[ \frac{\tau_m(x, \tau) - \tau_a}{\tau_a - \tau_{pb}} = \frac{erf \frac{x}{\sqrt{\tau_{pb}}} \delta}{erf \delta} \]  

(17)

where \( erf \) – the tabulated Gauss error function;

\( \delta \) in the solid zone

\[ \frac{\tau_s(x, \tau) - \tau_a}{\tau_{pb} - \tau_a} = \frac{1 - erf \frac{x}{\sqrt{\delta_{pb} / \delta_m}}}{1 - erf \delta (P \sqrt{\frac{\delta_{pb}}{\delta_m}})} \]  

(18)

The law of moving phase boundary:

\[ \delta(\tau) = 2P \sqrt{\alpha_p \cdot \tau} \]  

(19)

The velocity of the phase at time

\[ \frac{d\delta}{d\tau} = (2P \sqrt{\alpha_p \cdot \tau})^{\frac{3}{2}} \]  

(20)

In the expressions \( P \) – dimensionless quantity determined from the transcendental equation [8].

The problem is simplified if the solid zone initially has a phase transition temperature \( \tau_s = \tau_{pb} \).

While the heat transfer in the solid zone is not observed in the balance equation at the interface \( dQ = 0 \). If we assume that the temperature field in the molten layer at any time corresponds to the stationary one (the process is quasi-stationary), then the temperature distribution in the molten layer \( \delta(\tau) \) is linear, as in the infinite plate thickness \( \delta \) at the stationary thermal conductivity [8-9], that is, to determine the temperature at any point of the molten layer, you can use the equation

\[ \frac{\tau_a - \tau_p(x, \tau)}{\tau_a - \tau_{pb}} = \frac{x}{\delta(\tau)} \text{ where } 0 \leq x \leq \delta(\tau) \]  

(21)

Transforming the formula for the speed of phase movement through the phase transition criterion, we will have the formula for the speed of movement of the phase boundary [7-11]:

\[ \frac{d\delta}{d\tau} = \frac{\sqrt{\rho_p(t_a - \tau_{pb})}}{2\alpha_p} \]  

(22)

The expressions for the velocity dependence are valid for the equality \( \tau_s = \tau_{pb} \) and for the linear temperature distribution in the molten layer they are an important special case of Stefan's solution [8–10].

It is known that at moderate speeds in a very thin layer of the melt quasi-stationary approximation is quite acceptable. Physically, this corresponds to the assumption that the heat removed from the molten layer during its heating from the phase transition temperature \( \tau_{pb} \) to some average specified temperature at a given time is very small compared to the heat that went to the phase transition of the layer from the solid state to the molten state.

In this solution, the boundary condition on the external heated surface \( x = 0 \) is written as a boundary condition of the first kind. For engineering practice, the case is more interesting when the specified temperature is not the surface temperature, but the temperature of the heated medium, in this case the plasma jet \( \tau_{pb} \), i.e. the boundary condition of the third kind. In this case, in the quasi-stationary approximation for the law of the phase boundary displacement, we obtain

\[ \delta(\tau) = \frac{2\lambda_p(t_p - \tau_{pb})^2}{H} \frac{\lambda_p}{\alpha_p}, \]  

(23)

where \( \alpha_p \) – the heat transfer coefficient of the plasma.

Since the thickness of the molten layer cannot be less than zero, then at \( \delta(\tau) = 0 \) we find the time before melting:

\[ \tau_0 = \frac{\lambda_p H}{2\alpha_p} \left( t_p - \tau_{pb} \right) \]  

(24)
3. Conclusion
Thus, under the boundary conditions of the third kind, in contrast to the boundary conditions of the first kind, the maximum value of the velocity of the phase boundary corresponds to the condition $\tau = \tau_0$ and has a finite (and not infinitely large) value, then with increasing $\tau$ the velocity decreases, so that at $\tau \to \infty$, $d\delta/d\tau = 0$.

The practical application of the plasma spraying process with preliminary local melting by periodic exposure to a single-phase plasma jet lasting until the moment of melting increases the adhesion strength of the sprayed layer with the base.

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