THE INVESTIGATION OF THE TEMPERATURE FIELD IN THE THICKNESS OF THE BASE FOOD INDUSTRY MATERIALS SPRAYED IN A PLASMA JET

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Abstract: This article presents the temperature field distribution outside and inside of the base material and the surface heating of the base material to the melting temperature. The high adhesion of the base material to the coating formed by plasma spraying is obtained in the case of a re-melting and subsequent crystallization of the superficial layers. Interaction of the molten particle with the re-melted surface of the base material ensures the high quality of the coatings. By suggesting values of the melting depth of the superficial layer of the base material, we determine the spent time under the action of the plasma jet.

Keywords: Powder, friction coupling, plasma jet, compatibility.

Introduction

The quality of the plasma-sprayed layers depends not only on the heat transfer conditions between the spray-dispersed particles and the plasma, but also on the direct heat exchange of the plasma-treated surface and the particles themselves. Previously, the heat exchange between particles and plasma was considered, also the heating and melting regime and the formation of a temperature field. Undoubtedly, the state of the dispersed particle before the contact with the surface of the base material greatly determines the quality of the applied layer [5,6].

This condition is necessary but not sufficient. In order to obtain a high quality of the deposited layers, a good adhesion of applied material on the surface is required. This is only possible if the upper layer of the base material passes into the liquid phase and the interaction between the powdery material and the upper layer forms a solution (melt) of the two materials and a subsequent crystallization of this melt will ensure good adsorption[5, 6, 7, 8].

Modeling the process

The question is only in the quantitative image of this process. In this regard, we set the task of determining the temperature field in the base material. The heat exchange process can be divided into two stages.

Heating the sample from the initial temperature T0 to the Tcr crystallisation temperature under the action of plasma and forming the solid-liquid phase transition zone. We admit the form of a plane surface, because the size of the pulverized material is much smaller than the characteristic size of the base material [2,3].

The second stage is the deepening of the phase action area in the thickness of the material. In order to solve the problem, we admit the thermo-physical coefficients constant and equal to the average value in the temperature range, their change occurs only in phase transformations.

In the first stage, we are dealing with the classic heat exchange for a semi-limited body [2,3].

$$\frac{dT}{d\tau}(x,\tau) = a\frac{d^2T}{d\,x^2}(x,\tau); \qquad \tau>0; \qquad 0<x<\infty, \tag{1}$$

$$\mathrm{T\ (x,\ 0\ )=\ T0}, \tag{2}$$

$$\lambda_1\frac{dT}{dx} = -\alpha[T_{\text{пл}} - T(0,\tau)], \tag{3}$$

$$T(\infty,\tau)=T0; \qquad \frac{dT}{dx}(\infty,\tau) = 0, \tag{4}$$

For the second stage, the formulation of the problem becomes somewhat more complicated. The given system can be considered an infinite cylinder, surrounded by a thin coating. The role of the coat is played by the molten upper layer. The heat transfer between two bodies takes place after Newton-Richman's law. The thin coating of the melt will be considered flat. We admit that the second stage is similar to the first. Then our problem can be written as follows:

$$\frac{dT_2}{d\tau} = \alpha_2\frac{d^2T}{dR^2} \qquad (\tau > 0\,;\ R_1 \le r \le R_2) \tag{5}$$

$$\frac{dT_1}{d\tau} = \alpha_1\left(\frac{d^2T_1}{d\,R^2} + \frac{1}{R}\frac{dT_1}{dR}\right) \qquad \tau > 0; \qquad 0 \le R \le R_1, \tag{6}$$

$$-\lambda_2\frac{dT_2}{dR}(R_2,\tau) + \alpha[T_{\text{пл}} - T_2(R_2\tau)] = 0, \tag{7}$$

$$T_1(R,\tau) = T_2(R,\tau) = T_\xi\ , \tag{8}$$

$$\lambda_1\frac{dT_1}{dR}\bigg|_{R=1} - \lambda_2\frac{dT_2}{dR}\bigg|_{R=R_1} = L\rho\frac{d\xi}{d\tau}\,, \tag{9}$$

The problem solution for the first period is solved by the operational method [1.2.3] and written as:

$$\frac{T_1-T_0}{T_{\text{пп}}-T_0} = erfc\frac{x}{2\sqrt{a_1\tau}} - e^{\frac{\alpha}{\lambda_1}x+\frac{\alpha^2}{{\lambda_1}^2}a_1\tau}\cdot erfc\left(\frac{1}{\sqrt{a_1\tau}} + \frac{\alpha}{\lambda}\sqrt{a_1\tau}\right), \tag{10}$$

The Gauss error function

$$erfc\frac{x}{2\sqrt{a\tau}} = 1 - erf\frac{x}{2\sqrt{a\tau}} = \frac{2}{\pi}\int_x^\infty e^{-\frac{x^2}{2\sqrt{a\tau}}}\cdot d\left(\frac{x}{2\sqrt{a\tau}}\right), \tag{10.1}$$

There are two phases in the second stage: a melt and a solid product; the first sector constitutes the liquid surface and the second sector is represented by liquid-solid phase transformations. The temperature distribution in the liquid phase of the substance will be denoted by T2 and in the solid phase by T1. In our case, the equation is written as: (1) but the argument value is 0 <x ≤ ξ. where ξ is the phase transformations coordinate, the boundary condition (2) will take the form:

$$\lambda_2\frac{dT_2}{dx}\,|_{\,x=0} = -\alpha(T_{\text{пл}} - T_{\text{п}}), \tag{11}$$

$$T_2(x_1\tau_1) = T_\xi, \tag{12}$$

Where Tп – the surface temperature. Assuming that the melt thickness is R2 – ξ ≤ R1, the surface layer problem can be considered to be smooth. Therefore, the problem is formulated as follows:

$$\frac{dT_1}{d\tau} = a_1\frac{d^2T_1}{d\,R^2} + \frac{1}{R}\,\frac{dT_1}{dR}; \qquad \tau > \tau_1; \qquad 0 \le R \le R_1, \tag{13}$$

$$\frac{d\,T_2}{d\tau} = a_2\frac{d^2T_2}{d\,R^2}; \qquad \tau > \tau_1; \qquad \xi \le R \le R_2, \tag{14}$$

Taking into account the limit conditions (11), (12), (8) using the Laplace transformation [1.2.3.4], we obtain the temperature distribution as:

$$\frac{T_1(R_1\tau)-T_\xi}{T_{пл}-T_0} = 1-\sum_{n=1}^{\infty}\cdot A_n\cdot I_0\left(\mu_n\frac{R}{R_1}\right)exp(-{\mu_n}^2 F_0), \quad (15)$$

$$\frac{T_2(R_1\tau)-T_\xi}{T_{пл}-T_\xi} = 1-\sum_{n=1}^{\infty}A_n\left\{I_0(\mu_n)cos\left[\mu_n k_a^{\frac{1}{2}}\left(\frac{R}{\xi}-1\right)\right]-k_\varepsilon I_1(\mu_n)sin\left[\mu_n k_a^{\frac{1}{2}}\left(\frac{R}{\xi}-1\right)\right]\right\}exp(-\mu_n^2F_0), \quad (16)$$

Where μn – The roots of the characteristic equation

$$I_0(\mu)\left[B_i\,cos\,k_a^{1/2}(k_R-1)\mu-k_a^{1/2}k_R\mu\sin k_a^{1/2}(k_R-1)\mu\right]-k_\varepsilon I_1(\mu)\left[B_i\sin k_a^{\frac{1}{2}}(k_R-1)\mu+k_a^{\frac{1}{2}}k_R\mu\cos k_a^{\frac{1}{2}}(k_R-1)\mu\right]=0, \quad (16.1)$$

$$A_n=\frac{2Bik_\varepsilon\left[k_a^{\frac{1}{2}}(k_R-1)\mu_n+Bi\cdot tgk_a^{\frac{1}{2}}(k_R-1)\mu_n\right]}{\mu_n\cdot I_0(\mu_n)\sin k_a^{\frac{1}{2}}(k_R-1)\mu_n}\cdot\left\{[k_\varepsilon^2\cdot k_a(k_R-1)^2\mu_n^2+Bi^2]ctgk_a^{\frac{1}{2}}(k_R-1)\mu_n+\frac{2k_a^{\frac{1}{2}}(k_R-1)\mu_n}{\sin 2k_a^{\frac{1}{2}}(k_R-1)\mu_n}\cdot[Bi^2+k_a(k_R-1)^2\mu_n^2]+\left[k_a(k_R-1)^2\mu_n^2+2k_\varepsilon k_a^{\frac{1}{2}}(k_R-1)Bi+k_\varepsilon^2Bi^2\right]tgk_a^{\frac{1}{2}}(k_R-1)\mu_n+k_\varepsilon k_a(k_R-1)^2\mu_n^2+2k_\varepsilon k_a^{\frac{1}{2}}(k_R-1)\mu_nBi-2k_a^{\frac{1}{2}}(k_R-1)\mu_nBi-\frac{k_\varepsilon Bi^2}{\mu_n}\right\}^{-1}, \quad (16.2)$$

For large values of α, the solution (16) is simplified and written as:

$$\frac{T_2(R,\tau)-T_\xi}{T_m-T_\xi}=1-\sum_{n-1}^{\infty}\frac{2\cdot\sin\left[k_a^{\frac{1}{2}}\left(k_R-\frac{R}{\xi}\right)\mu_n\right]\exp(-\mu_n^2F_0)}{\left[\frac{k_\varepsilon^2-1}{k_\varepsilon}\ \sin^2k_a^{\frac{1}{2}}(k_R-1)\mu_n-\frac{1}{2\mu_n}sin2k_a^{\frac{1}{2}}(k_R-1)\mu_n+C\right]}, \quad (17)$$

$$c=k_a^{\frac{1}{2}}(k_R-1)+\frac{1}{k_\varepsilon}.$$

The speed of advancement of the transition phase is determined by replacing equation (17) and (15) in (9). The value of the k_a, k λ, k_ε parameters is defined as the following relation: $k_a = a_1 / a_2$ – characterizes the inertial properties of the first environment to the second; k λ = λ1 / λ2 is the relative thermal conductivity of the environment:

The thermal activity of the first environment compared to the second. Equations (16) or (17) differ from equation (10) not only through the material parameters but also the shape parameters, since in the latter case the solution is given for a body of limited size (the penetration area is small compared to the characteristic dimension of the object, solution for a semi-limited object.

The value of $I_0\left(\mu_n\frac{R}{R_1}\right)$ – is the Bessel function, of the first type, zero order:

$$I_0\left(\mu_n \frac{R}{R_1}\right) = I_0(U) = \sum_{k=0}^{\infty} \frac{(-1)^k \left(\frac{U}{2}\right)^{2k}}{k!(k+1)} \qquad (18)$$

In this sense, the speed of advancement of the transition phase area will be written as:

$$\frac{d\xi}{d\tau} = \frac{1}{L\rho}\left\{(T_{\text{пл}} - T_0)\lambda_1 \sum_{n=1}^{\infty} \frac{A_n(-1)^k k\left(\frac{\mu_n R}{R_1}\right)^{2k-1}}{k!(k+1)} exp(-\mu_n^2 Fo)\Big|_{\xi} + \left(T_{\text{пл}} - T_{\xi}\right)\lambda_2 \sum_{n=1}^{\infty} A_n \left\{I_0(\mu_n)\left[-\sin \mu_n k_a^{1/2}\left(\frac{R}{\xi} - 1\right)\mu_n \frac{k_a^{1/2}}{\xi} - k_{\varepsilon} I_1(\mu_n) cos\mu_n k_a^{1/2}\left(\frac{R}{\xi} - 1\right) \cdot \mu_n \frac{k_a^{1/2}}{\xi}\right]\right\}\Big|_{\xi} \exp(\mu_n^2 Fo)\right\} \qquad (19)$$

$$I_1\left(\mu_n \frac{R}{R_1}\right) = I_1(U) = \sum_{k=1}^{\infty} \frac{(-1)^k \left(\frac{u}{2}\right)^{1+2k}}{k!(1+k+1)}; \qquad (20)$$

Experimental research Experimental research has shown the following results presented in figures 1,2,3.

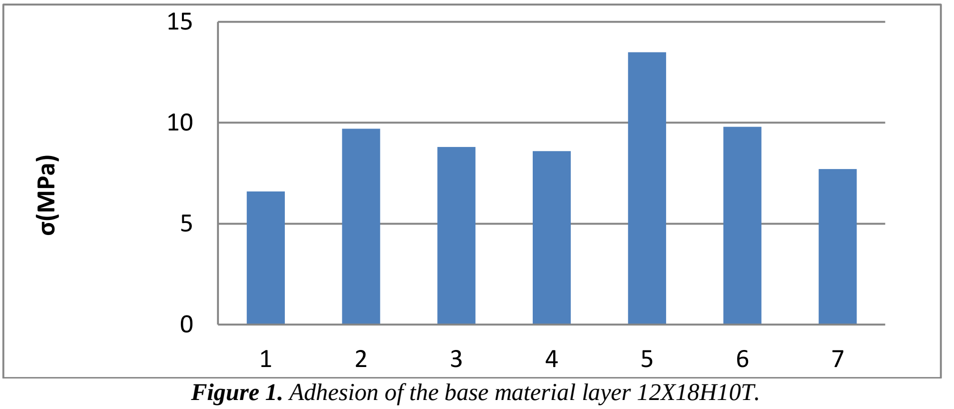

Figure 1. *Adhesion of the base material layer 12X18H10T.*

Layer: 1 – Al2O3+10%Al with intermediate layer ПН85Ю15; 2 – Steel P6M5K5 with intermediate layer ПН85Ю15; 3 – Al2O3+10% Al with intermediate layer ПТ-НА-01; 4 – gAl2O3+30%Al with intermediate layer ПТ-НА-01; 5 – ПС-12НВК-01 with intermediate layer ПТ-НА-01; 6 – 50%ПН55Т45-50% TiC without intermediate layer; 7 – ПТ-АН9 without intermediate layer.

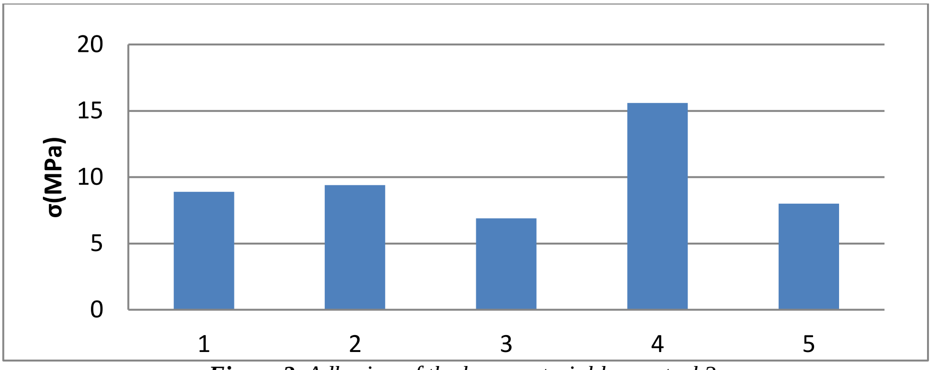

Figure 2. *Adhesion of the base material layer steel 3.*
Layer: 1 – 90%Al2O3+10%Al with intermediate layer ПТ-НА-01; 2 – 70% Al2O3+30%Al with intermediate layer ПТ-НА-01; 3 – СГ-Т(п) with intermediate layer ПТ-НА-01; 4 – ПС-12НВК-01 with intermediate layer ПТ-НА-01; 5 – ПГ-АН9 without intermediate layer

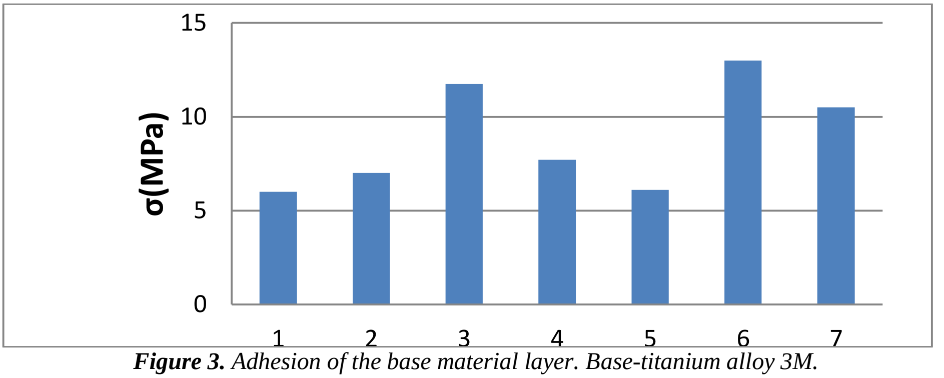

Figure 3. *Adhesion of the base material layer. Base-titanium alloy 3M.*
Layers: 1 – СГ-Т(п) with intermediate layer ПТ-НА-01; 2 – Al2O3+10%Al without intermediate layer; 3 – ПС-12НВК-01; 4 – ПТ-19Н-01 with intermediate layer ПТ-НА-01; 5 – Al2O3 without intermediate layer; 6 – ПН55Т45 without intermediate layer; 7 – 50%ПН55Т45+50% TiC without intermediate layer;

Conclusions

1. The materials sprayed with layers ПГ-СР2; ПС-12НВК 01; СНГН-50; ПН55Т45; СГ-Т (П); ПН55Т45 50% + 50% TiC; ТС-Т (Р) + 20% TiC and others on the base carbon steel 3 material, 12Х18Н10Т stainless steel, 3M titanium alloy is use-wear proof layers high adherence, provided at well-defined technological regimes at УПУ-3Д and ОВ-1955.
2. The adhesion of the base material to the plasma-spray coatings is achieved in the case of a retrieval and subsequent crystallization of the superficial layers.

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