Calculation of parameters of particles in a plasma jet and modeling of kinematic modes of spraying of wear resistant material

S N Sharifullin\textsuperscript{1,2}, G I Trifonov\textsuperscript{3,4}, I N Vyachina\textsuperscript{5}

\textsuperscript{1}Kazan Federal University, Russia
\textsuperscript{2}Kazan state agrarian University, Russia
\textsuperscript{3}Voronezh state technical University, Russia
\textsuperscript{4}Air force Academy named after Professor N. E. Zhukovsky and Y. A. Gagarin, Russia
\textsuperscript{5}Naberezhnochelninsky Institute, Kazan (Volga) Federal University, Russia

Email: Saidchist@mail.ru

Abstract. In this article the calculations on the strength of the coupling halves of the CV joint by the finite element method in the system of APM FEM. This calculation method is a method of creating a mathematical model and method of investigation. The assigned technological parameters of plasma spraying, namely, the estimated capacity of the plasma generator is 50 kW, and reach air temperature at the output of 3000 K, and the corresponding enthalpy of 3.8 \times 10^6 \text{j/kgK}. Based on the analysis of the wear of the contact surfaces of the coupling halves, and also carried out strength calculations, was chosen as the material for plasma spraying – tungsten carbide. Developed mathematical model to determine the temperature of the powder particles and their velocities in a plasma jet. Based on the earlier dependence of the kinematic regimes of plasma spraying, the resulting system of equations for the kinematic modes that enable you to organize control of the kinematics of the deposition process details with the internal spherical surface.

Key words: speed of the plasma jet, the temperature of the sprayed particles, kinematic modes, plasma spraying, mathematical modeling

1. Introduction

Today, there are a large number of chemical, galvanic and physical methods for applying wear-resistant, heat-resistant, corrosion-resistant and other coatings that enhance the performance properties of the surfaces. A detailed analysis of a particular method or method in a scientific article is impossible, so it was decided to choose a promising area to establish reliable, durable and wear-resistant coatings, namely, plasma spraying \cite{1, 2}.

The aim of this work is the simulation of mathematical model calculate the velocity and temperature of the composite powder in the stream of the air plasma. The output of the system of equations for the kinematic modes of plasma spraying to the inner spherical surface of the coupling half.
2. Materials and methods of research

As a parts representative for coating was chosen as the spherical coupling of the hinge of equal angular speeds, the 3D model of which is shown in Fig. 1. To confirm and verify the appropriateness of applying a plasma spray coating on the inner spherical surface of the half couplings, were calculated by the finite element method in the system stress analysis APM FEM program KOMPAS-3D V15.1. This calculation method is a method of creating a mathematical model and method of investigation.

![3D model of spherical coupling](image)

- a – model coupling half; b – finite element mesh; v – the total linear displacement; g – factor of safety for strength; d – safety factor for yield strength

**Figure 1** – Results of strength calculation of the APM FEM program KOMPAS-3D V15.1

To solve this problem it is necessary to determine the change similar parameters for the plasma jet created in a plasma torch. The estimated capacity of the plasma generator is 50 kW. Achieved temperature at the output of 3000 K. The Corresponding enthalpy of 3.8·10^6 J/kgK [3]. The thermal efficiency of the plasmatron 70%. Air flow of plasma-forming G = 9 g/s.

The choice of material of the deposition surface of parts produced with the help of table 1, which presents a selection of materials functional coatings [4].

| The coating material | Characteristic of the surface layer, improving a coating |
|----------------------|------------------------------------------------------|
| Al₂O₃, Al-Ni, Ni-Ti, Mo, Cr₂O₃, Cr, WC, MgAl₂O₄ | Durability |
| Al, Al₂O₃, Cr, Ti, Zn, Cr₂O₃, Al₂O₃-TiO₂ | Corrosion resistance |
| Al₂O₃, ZrO₂, Al-Ni, Mo, ZnB, MgAl₂O₄ | Temperature Resistance |
| ZrO₂, WC-CO, TiC, Cr₂O₃, Cr-B-Ni | Erosion resistance |
| W, Mo, WC, Cr-Ni, MoSi₂, MgAl₂O₄ | The heat resistance |
| Al-Ni, Ti-Ni, Al₂O₃, ZrO₂ | Intihuatana mobile nodes |
| Al₂O₃, NiSi₂, Al-Ni, ZrO₂ | Heat insulation |
| Al₂O₃, BaTiO₃, SiO₂, MgO- Al₂O₃ | Electrical isolation |

Based on the analysis of the main types of wear undergone by the inner spherical surface of the coupling hub, was selected as the sprayed material is tungsten carbide.
3. The study and results

The speed of the sprayed particles is the subject of experimental study. Therefore, to compare data obtained from different researchers in this field, it is not possible because the experiments were carried out on different equipment and under certain laboratory conditions. In this regard, we propose a mathematical approach to determination of the velocity of sprayed particles.

Determine the speed of the powder \[ W_p = W \sqrt{\frac{3 \rho_p C_s}{2 \rho d_p^2} x} \] (1)

where \( \rho \) – the density of the air at the appropriate temperature, kg/m\(^3\); \( \rho_p \) – the density of tungsten carbide (15.63 g/cm\(^3\)); \( d_p \) – size of powder (\( \mu \)m); \( x \) – distance from nozzle exit (m); \( C_s \) - the drag coefficient.

Modeling the motion of particles of tungsten carbide powder in a plasma jet is taken that the tungsten carbide is spherical in shape.

Then \( C_s = \frac{24}{Re} \), where \( Re \) – Reynolds number. In this case \( Re = \frac{Wd_p}{\nu} \), where \( \nu \) – the kinematic viscosity coefficient. Given these equations, equation (1) becomes:

\[ W_p = 6 \sqrt{\frac{W \rho_p \nu}{\rho d_p^2} x} \] (2)

Determining the temperature of the sprayed particles in plasma spraying should be carried out with the radius of the particles and changes in material properties along the radius.

Heating of the particles of the powder material of tungsten carbide was seen in the assumption of their spherical shape, which is justified by the micron size of particles and their rotation due to asymmetrical entry of the powder into the plasma jet.

The temperature of the sprayed particles was found from the equation of heat transfer of powder particles with the gas. After mathematical modelling of process of heating the tungsten carbide powder, was obtained the equation for the temperature of sprayed particles:

\[ T_p = T - e^{-\frac{6Nu \lambda}{\rho_p d_p^2 C_p} \tau + \text{const}} \] (3)

where \( \lambda \) – coefficient of thermal conductivity, W/mK; \( C_p \) – the heat capacity of tungsten carbide; \( \tau \) – the movement of the particles. It is worth considering that \( \tau = \frac{2x}{W_p} \), a \( Nu \) – the Nusselt number in the flow of the ball, in this case \( Nu = 2 + 0.03 \Pr^{0.33} Re^{0.51} 0.35 \Pr^{0.35} Re^{0.58} \) [6], где \( \Pr = \frac{\nu C_p}{\lambda} \) (Prandtl number).

Knowing that reach the temperature output of 3000K, and the melting point of tungsten carbide 3143K, then deal with the case when the particles are two-phase state, that is composed of two layers: the inner (solid) and outer (liquid). As further heat supply boundary melting is shifted inwards. In the end, during the deposition of tungsten carbide on the surface of the solid layer in the form of tungsten particles settle to the bottom border of the sprayed layer due to its density and phase state, and the carbon and all related impurities and gases rise to the upper level of the sprayed layer (carbon glass).

Kinematic regimes of plasma spraying, namely, the speed of rotation of the coupling halves \( \frac{d\phi}{dt} \), the longitudinal moving speed of the plasma torch \( \frac{dz}{dt} \), the radial speed of the plasma torch \( \frac{d\rho}{dt} \) and
the contour speed of the plasma torch $S_k$, in this case, the plasma spraying of the inner spherical surface after the process simulation and mathematical transformations, drawing on the work of [6], will take the form of:

$$\frac{d\varphi}{dt} = \frac{v}{\sqrt{(\tan \varphi z)^2 + \beta^2}}$$

$$\frac{d\rho}{dt} = \frac{ns}{\sqrt{(1 + \tan \varphi z)^2}}$$

$$\frac{dz}{dt} = \frac{ns}{\sqrt{(1 + t \tan \varphi z)^2}}$$

(4)

$$s_k = sn$$

where $v$ – the speed of the sprayer relative to the surface, $\psi$ – the angle between the tangent and forming a body of revolution at the current point and the axis $z$; $\beta$ – the pitch of the spiral path of the spot deposition on the surface; $n$ – the number of revolutions of the main drive; $s$ – the reverse flow. It should be noted that the cylindrical $z$ coordinate for the spherical surface of the half-coupling is expressed by the equation [7]:

$$z = \frac{\varphi \beta}{\sqrt{1 + \tan \varphi z^2}}.$$  

(5)

The number of revolutions of the main drive is given by:

$$n = \frac{60v}{\sqrt{(2\pi k z)^2 + s / (1 + \tan \varphi z^2)}}$$

(6)

4. Conclusions

1. The developed mathematical model allows to determine the temperature of the powder particles, for example, tungsten carbide, and their speed in a plasma jet.
2. Based on the earlier dependence of the kinematic regimes of plasma spraying, the resulting system of equations for the kinematic modes that will allow to systematize the management of the kinematics of the deposition process details with internal spherical surface.

References

[1] Lomuhin VB Sharifullin S N and Lapteva I V 2016 J. Phys.: Conf. Series 669 012051.
[2] Kornienko E E, Lapushkina E J, Kuzmin V I, Vaschenko S P, Gulyaev I P, Kartaev E V, Sergyachev D S, Kashapov N, Sharifullin S, Fayrushin I 2014 J. Phys.: Conf. Ser. 567 012010
[3] Vargaftik, N. B. Handbook on thermophysical properties of gases and liquids. Second edition, revised and supplemented /N. B. Vargaftik. – M.: "Nauka". – 1972. – 720 p.
[4] Trifonov, G. I. Influence of plasma spraying of composite powder materials on the wear resistance of machine parts [Electronic resource] /G. I. Trifonov, S. Y. Jackin //MASTER’S JOURNAL, Perm national research Polytechnic University, 2017. – Pp. 30-36.
[5] Ilyushchenko, A. F., the Processes of forming thermal spray coating and modeling /A. F. Ilyushchenko, A. I. Shevtsov, V. A. Okovity, G. F. Gromyko. – Minsk: Belarus. Science, 2011. – 357 p.
[6] Kutateladze, S. S. Fundamentals of the theory of heat transfer. Fifth edition, revised and enlarged /S. S. Kutateladze. – M.: Atomizdat. – 1979. – 416 p.
[7] Puzriakov, A. F. Theoretical bases of technology of plasma spraying. Proc. manual for the course "Technology of structures made of metal composites". Second edition, revised and enlarged /A. F. Puzriakov. – M.: Publishing house of Moscow state technical University named after N. E. Bauman. – 2008. – 360 p.