THE NEW PLASMA EQUIPMENT FOR SUPERSONIC SPRAYING

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Abstract

The new approach to building the supersonic plasma powder spraying has been developed in view of the current trends. The approach is based on using a variable-composition mixture of gas and air and a stabilized elongated electric arc that burns in a plasmatron and is adapted to meet the technology requirements. Cost effectiveness and technical expediency of using air-gas mixtures are especially pronounced under the current conditions of increasing plasmatron capacities and transition to supersonic velocities, where optimal parameters are shifted toward high plasma gas flow rates and time of contact of particles with the environment is reduced.

1.0 Mathematical modelling

The mathematical model of the processes occurring in the plasmatron nozzle during thermal spraying consists of two independent parts. The first part involves theoretical description of the supersonic plasma flow in the cylindrical channel (nozzle exit section), which comprises the electric arc in the region near its axis. The second part is associated with investigation of motion and heating of the powder fed into the nozzle by lateral (normal to the axis) injection, as well as estimation of the position of a point of splitting of the molten particle under the effect of aerodynamic forces of the carrier flow. The mutual effect of the particles and their coagulation are taken into account, the bulk concentration of the powder in the flow being sufficiently large.

The problem of transition through the sound velocity uses a well-known idea of a decisive role of the boundary layer for the flow inside the cylindrical channel [1,2], where the model of transition through the sound velocity is considered for a plasma arc flow in the Laval nozzle without allowance for the effect of the boundary layer. The flow in a radial direction is conditionally divided into the near-axis region of pressing out of the arc with section Θ_d, region of pressing out of the boundary layer with thickness δ^* and the unidimensional, non-viscous and adiabatic “external” flow with an adiabatic index of $\gamma = 1.4$, which is located between the above two regions.

The bound of the region of pressing out of the boundary layer plays the role of the Laval nozzle wall [3]. The boundary layer in a longitudinal direction is divided into a region of growth which ends in section X_t, and a region of “reset” in which thickness δ of the layer decreases from a maximum value of $\delta_m = \delta(X_t)$ to a value of $\delta_a = 0$ at the nozzle exit section. In [3] the longitudinal profile of the nozzle and its “boundary” point X_t are assigned and the sound point X_s is the point to be found. In this problem the situation is reverse: position of the sound point is taken from experiments, while the profile of the pressing out region bound and, in particular, the position of point X_t are calculated.

According to [3], $X_t < X_s$, i.e. the region of growth of the boundary layer is in the subsonic area of the flow. Therefore, in this region the $\delta(X)$ relationship is assumed to be as follows [4]:

$$\delta/(X-b) = 4{,}6\ Re_x^{-0{,}2}, \qquad Re_x = [\rho_\infty u_\infty/\mu_\infty](X-b), \tag{1}$$

which is valid for the required boundary layer in the case of the surface being blown over with an uncompressible air flow. Here ρ_∞, u_∞ and μ_∞ are the density, velocity and viscosity of the external flow. Hence, assuming that $\delta^* \approx 0.13\delta$, for the pressing out thickness in the region of its growth we will have the following relationship:

$$\delta^* = C(X-B)^{0,8}, \quad C = 0,598(\mu_\infty/\rho_\infty u_\infty)^{0,2}, \ X \le X_t \tag{2}$$

from which it follows that part of the flow occurring outside the boundary layer pressing out region depends upon the X section as follows:

$$A(X) = F[1-2\delta^*(X)/R], \qquad X \le X_t \tag{3}$$

Here R is the radius of the outlet cylindrical portion of the nozzle, $F=\pi R^2$.

Because the model is of the estimation, in (1) for a specific pulse we used its value at the sound point $(\rho_\infty u_\infty)_s$, while for viscosity we used the value of $\mu_\infty(300\text{ K}) = 1.81\cdot10^{-5}$ Pa.

$$\delta^* = \delta^*_m - [(X-X_t)/(a-X_t)]^\chi, \qquad X \ge X_t, \qquad \chi > 1 \tag{4}$$

Here X_t and χ are the parameters to be determined. As compared with the problem considered in [3], they are additional parameters. Therefore, we used two experimental facts taken from [5], which were established for ranges of variations in working parameters and nozzle geometry close to those under consideration: distance of the sound point from the nozzle exist section and Mach number of the flow at the exit section can be considered permanent and equal to:

$$a - X_s \approx 0,8\ R, \qquad M \approx 1,3.$$

Section $A(X)$ at $X > X_t$ is related to δ^* by the same relationship (3) as at $X \le X_t$. Considering the above-said and based on the approach used in [3], we obtain the system of equations for dimensionless values $\xi_t = X_t/X_s$ и χ:

$$\begin{aligned} \chi &= K_1(1-\xi_t)/[K_2(\xi_t - K_3)^{0,8} - 1] \\ \chi &= \ln\{1-[1/K_2(\xi_t - K_3)^{0,8}]\}/[(1-\xi_t)/(K_4-\xi_t)] \end{aligned} \tag{5}$$

Here $K_1 = [1-\Theta_{ds}/A_s] / [n(\Theta_{ds}/A_s)(1-A_s/F)]$

(index s designates the values at the sound point), where n is the parameter taken from [3],

$K_2=2CX_s^{0,8}/R(1-A_s/F)$,

where C is the constant taken from [1],

$K_3 = b/X_s, \quad K_4 = a/X_s$.

The unknown values of Θ_{ds}/A_s and A_s/F are determined preliminarily by solving equations from [3].

Equations of two-dimensional dynamics of particles injected in a normal direction into the axially symmetrical flow take into account, in addition to the aerodynamic force F_a, also the Suffman force [6], the effect of which on particles is directed along the radius of the flow to its axis. For a frontal expansion coefficient, we use the V.M.Puzyryev's formulae:

$$C_{\text{Д}} = \begin{cases} C_{\text{До}}/[1-0,00673\gamma^{0,5}(Re-24)MC^0_{\text{Д}}], & Re < 24 \\ C_{\text{До}} + 0,00299(Re-24)M, & 24 < Re < 100 \\ C_{\text{До}} + 0,00079(Re+187,6)M, & Re > 100, \end{cases}$$

Where γ is the adiabatic index of the flow, $Re=\delta V_r\rho/\mu$ is the Reinolds number for a particle with a diameter of δ, $M = V_r/a$ is the Mach number of the particle, $V_r = |\vec{V} - \vec{Vp}|$ is the relative velocity, $\vec{V}$, $\vec{Vp}$ velocity of the flow and particle, $C_{До}$ - approximation of the standard curve is set by the equation:

$$C_{До} = 24Re^{-1}(1 + 0,15Re^{0,687}), \qquad Re < 700$$

Heat exchange between the flow and the particle is calculated from the Nusselt number as follows:

$$Nu = 2\lambda_w/\lambda + 0,6Re^{0,5}Pr^{0,33}(\rho\mu/\rho_w\mu_w)^{0,2},$$

where index w indicates that the calculations are made at a temperature of the particle surface, Pr is the Prandtl number.

Splitting of the molten particle is determined by the Weber number $We = \delta\rho V_r^2/\sigma$ and the Laplace number $Lp = \delta\rho_P\sigma/\mu_P^2$, where σ, ρ_P, μ_P are the tension coefficient, density and viscosity of the particle. Upon reaching a critical value of the Weber number $We_c = 10$, the molten particle starts splitting in time

$$t_i = [2,6(1\text{-}3/2Lp^{-0,37})t_*/(\lg We)^{0,25}, \qquad t_* =(\delta \sqrt{\rho^*/\rho})/V_r$$

Numerical investigations in the first part of the above model concern parameters of the boundary layer at the exit section of the channel for short nozzles, where the boundary and arc layers do not yet join along the length of the nozzle. For the calculations the set values include braking pressure P_o and axial temperature T_m at the exit section of the nozzle, then power corresponding to this temperature and Joule heat released per unit length of the arc. Then the coefficients K_i, $i = 1,4$ from (5) are calculated and the system of equations (5) is solved. The calculation results show that coordinate X_t of the maximum thickness of the boundary layer is localized near the exit section of the nozzle for all available variants of conditions and nozzle geometries.

In calculation of motion and heating of the particles the parabolic profiles of axial velocity and enthalpy of the flow are as follows:

$$u/u_m = (h-h_w)/(h_m-h_w) = 1 - (r/R)^2$$

with values u_m, h_m, h_w constant in X. The values of $T_m = (1\div1,2)\cdot10^4$ K, $T_w = 400$ K were assumed for the temperature at the axis.

The velocity u_m was found from the value of $u_m = u_s(T_m)M$. The Mach number $M = 1.3$. Except for the density, thermodynamic and thermal-physical properties of the flow were taken from the Tables for a pressure of $P = 10$ MPa.

The calculations were made for particles of different materials and sizes ranging from 20 to 150 μm. The method of generation of the supersonic plasma flow under investigation provides the velocity of particles of all materials within a range of 700 to 900 m/s and their complete or partial melting. Increase in size of the sprayed particles and their velocity is accompanied by development of the processes of their aerodynamic splitting. Transition to the supersonic velocity promotes an increase in the concentration of particles in the flow. If a fraction composition of a powder used is sufficiently wide, it is necessary to take into account the effect of coagulation of the flying particles on properties of the coatings

2.0 Principles of building the supersonic plasma spraying equipment

Restrictions on the application of thermal spraying processes are associated primarily with an insufficient strength and reproducibility of properties of coatings. These drawbacks can be overcome to a significant degree by using the advanced supersonic spraying equipment.

An increase in the velocity of particles leads to a reduction of time during which they dwell in the jet up to the moment when they get to the substrate. On the one hand, this allows a degree of development of such undesirable phenomena as oxidation of the particles during their interaction with the environment (air) and thermal dissociation of the spraying material to be decreased. On the other hand, however, this reduces the possible time of heating the particles, which requires that powders with the particles of smaller sizes be used for supersonic spraying and that the jets formed provide a larger length of the heating zone.

Using a mixture of air and a hydrocarbon gas (methane, propane-butane) as the plasma-forming medium [5,7] allowed a practical commercial application in the 1980s of the new type of the "Kyiv-7" plasma machines. That was the equipment for subsonic plasma spraying, which played a substantial role in expanding the scales of utilization of this technology and output of parts with protective coatings.

Early in the 1990s, the Institute of Gas and the E.O.Paton Electric Welding Institute of the National Academy of Sciences of Ukraine developed and prepared for commercial application the new equipment "Kyiv-7S" for high-productivity supersonic plasma spraying with a capacity of 160 kW [8]. A large scope of comparative tests [5, 9, 10] showed that this equipment provided the best quality of thermal spray coatings, that it was cost effective, reliable and affordable for a wide circle of customers. However, this advanced development is not in demand in the independent states of the former Soviet Union.

This work is a result of efforts made by the authors in order to preserve this R&D area and impart a new practical significant to it.

According to the current concepts, to deposit dense coatings with a high adhesion strength, homogeneous structure and reproducible properties, it is necessary to have equipment which would make it possible to produce a concentrated flow of molten particles with a sufficiently high mean velocity at a minimum spread of temperatures and velocities. In addition, to increase the spraying process efficiency, the equipment should have a high productivity at a minimum level of power consumption and minimum losses of a spraying material, be convenient in operation and repairable.

The approach developed by the authors ideologically is based on the use of a mixture of air and a fuel hydrocarbon gas (methane, propane-butane) as the plasma gas and a stabilized elongated electric arc with a fixed mean length; and in terms of hardware it is based on the use of a plasmatron with a single inter-electrode insert (IEI) [11, 12].

The plasmatrons generating the reactive combustion products plasma use primarily an end thermochemical cathode with an (Hf, Zr) active insert (we also studied other versions, such as blind hollow copper or tungsten cathodes and cathodes which are continuously reduced from the gas phase) and provide a vortex arc stabilization. The role of vortex in the plasmatron is practically exhausted to fixation of the reference cathode spot of the arc and insulation (electrical and thermal) of the arc column in the IEI channel. Injection of part of the plasma gas to the gap of the IEI serving as the anode is required to increase dielectric strength and, accordingly, to eliminate break-through and formation of the twin arc, to create a gas curtain at the inlet of the channel of the nozzle - anode and equalize fields of the arc plasma parameters. As a result, this is accompanied by dissipation of the near-anode portion of the arc, localization of the anode zone of fixation in the narrow circular zone, rapid equalization of temperature, velocity and concentration fields behind the discharge fixation zone, splitting of the scale of turbulence and laminarization of the flow.

Two characteristic zones can be distinguished in the spraying plasmatron comprising the IEI. In the first zone there occurs conversion of the electric energy into the thermal one and formation of the optimal profile and level of parameters, such as the required temperature, velocity and concentration fields, allowing for averaged and pulsation components. The second zone is characterized by occurrence of formation of the two-phase flow determined by paths of the dispersed particles, acceleration and heating of the particles to their melting temperatures, as well as related physical-chemical transformations, such as evaporation, variation in chemical composition and size of the particles, as compared with the those of the initial powder.

Regions of the active local effect on the elongated electric arc in the spraying plasmatron are portions of the arc located near the cathode and anode. The arc channel length can be varied from 1 to 12 gauge lengths, depending upon the power requirement. At an arc current of 300 A, the electric power is 30 and 150 kW, respectively. The choice of geometrical ratios of the arc channel, parameters of the gas vortex and material of the channel walls should be based on conditions of ensuring spatial stability of the discharge burning, elimination of any random oscillations and breaks-through to the wall at a maximum intensity of the electric field and minimum heat losses. At small lengths of the IEI, up to 1-2 gauge lengths, where the heat losses to the channel wall are determined only by the arc radiation (they are decreased with a hydrocarbon gas added to air), it is advisable to arrange a recuperative cooling of the IEI with the plasma gas. In this case the efficiency of the plasmatron amounts to 90 %. At lengths of the IEI equal to 5-6 gauge lengths, the channel walls can be made from a material with a low calorific value (stainless steel, silicided graphite). At 6-12 gauge lengths, because of growth of the convective component and thermal conductivity of the combustion products plasma with a maximum temperature of about 3500 K (when this temperature is reached in a narrow circle between the arc plasma and the channel wall) the density of the heat flow becomes commensurable with a heat load of the output electrode - anode. This portion of the arc channel is made from copper and is intensively cooled. Further increase in length of the channel with a single IEI of more than 10-12 gauge lengths makes no sense, as heat released in the electric arc is no longer consumed for heating the gas but goes into the channel wall, and becomes technically unfeasible because of arc twinning.

Addition of a fuel hydrocarbon gas to air to blow the cathode leads to an increase in the arc voltage by 25-30 % and decrease in the cathode strength (if no precautions are made) by approximately the same value.

The found effect of a stronger influence of methane added to the gas (air, argon, nitrogen) to blow the cathode, than that in mixture with the basic plasma gas, on growth of the arc voltage allows the latter to be easily maintained at a constant level, the total fuel-to-oxidizer ratio being varied. As the flow rate of the gas used to blow the cathode is approximately 10 times lower than that of the plasma gas, and the effect on the arc voltage is stronger, the compensation for the voltage growth due to an increased consumption of methane in the plasma-gas mixture by an insignificant decrease in consumption of methane to blow the cathode has no influence on the total composition of the mixture. This regulation aimed at maintaining the arc voltage at a constant level, independently of the composition of the mixture, makes it possible to fully utilize the installed power of the power supply.

Stability of the near-cathode portion of the discharge in time and space is extremely important for the spraying plasmatron, as any pulsations or drift of parameters which might be formed here will be moved with the flow and have a substantial effect on characteristics of the arc as a whole and, naturally, on the generated plasma jet. The problem of increasing strength of the cathode and stabilization of parameters of the near-cathode portion of the discharge in the air-gas mixture is solved at a stage of starting up of the plasmatron, ensuring the optimal structure of the gas vortex and intensification of cooling of the cathode.

Starting up of the plasmatron with a thermochemical cathode, operating with the air-gas mixture, should be done so that a drop-type removal of material of the active insert of the cathode, burning out of the copper casing and arc twinning are eliminated.

Transition processes occurring when the plasmatron goes into the working conditions should ensure the subsequent long-time stable burning of the discharge.

The burning conditions with a drastically contracted arc spot was detected [5]. This is the case where the cathode works so that the emission film material evaporating under the arc spot is continuously reduced from the gas phase. Under these conditions during a long-time operation of the plasmatron there occurs no deepening of the arc into the cathode crater, which is attributable to evaporation of the material of the active insert. Therefore, there is no arc drift. This is one of the main factors of maintaining the plasma jet parameters which are reproduced in time.

In the near-anode portion of the arc, the processes that control formation of the plasma jet with the required parameters are combined with those that ensure stability of its long-time (not less than during one shift) generation.

The most efficient technique among all others widely known, for destruction of the stabilized arc and rapid filling of the profile of temperatures and velocities in the channel is to inject gas into the IEI gap - anode with an anti-vortex with respect to the basic plasma gas in an amount of 30-50 % of the total gas consumption.

Whereas an addition of a fuel hydrocarbon gas to air to blow the cathode leads to improvement of one properties (increase in voltage, decrease in energy output with radiation, expansion of the stable operation range) and deterioration of the others (increase in cathode erosion, degradation of the time stability of the cathode spot), the compensation for which requires special precautions to be made, an addition of CH4 to the near-anode portion leads to improvement of all properties. Localization of the discharge fixation zone is completed at a distance of 2 gauge lengths and the full filling of the profile is completed at a distance of 3 gauge lengths. A fundamental decrease (by an order of magnitude) in erosion of the anode is achieved by suppression of oxidation of copper and formation of the diffusion fixation of the arc to the anode in the combustion products plasma. This provides preservation of geometry of the nozzle during operation and plays a decisive role in practical application of the supersonic plasmatron.

Calculation-theoretical and experimental studies proved the possibility of ensuring the long-time (for more than 30 hours) stable generation of the elongated slightly under-expanded supersonic combustion products plasma jet, which provides high-productivity spraying of high-quality coatings of all groups of materials, using the sound nozzle. The range of the Joule heat release can be combined with the gas-dynamic critical range and that of free expansion. Phase transformations and heat exchange between the phases change parameters of the flow, but exert no effect on stability of the wave structure of the jet. The lateral injection of the sprayed powder into the supersonic plasma jet can be done in the gas-dynamic critical range (at a distance of approximately 0.6 gauge length to the nozzle exit section) or in the first "roll".

Technology peculiarities of spraying coatings with the combustion products plasma are associated with its thermal-physical properties [13]. The well filled profile of temperatures and velocities in the combustion products plasma jet and the extended high-temperature zone favour the efficient and uniform heating and acceleration of all particles of the powder, independently of their flight path. Combining air oxygen with the incomplete combustion products provides certain protection of the spraying material from oxidation in flight. A higher heat capacity of the plasma jet suggests the most efficient utilization of the combustion products plasma in processes where the efficient heating of a part is indicated. The optimal spraying distance is within a range of 200-300 mm. In the cases where it is required to avoid overheating of a part and coating, an extra cooling is used: air, carbon dioxide, water sprayer or droplet-air cooling.

In the processes of subsonic plasma spraying, the dominant is splitting of the powder particles with a size of about 50 ~m. In some cases of using the supersonic flows the dominant may be coagulation, where particles with a size much larger than those of the initial powder are found on the substrate of the coating. The process of supersonic plasma spraying is sensitive to fraction composition of the sprayed powder. To produce high-quality coatings, it is advisable to use a narrow fraction with a particle size of 20-40 ~m for ceramic powders and 20-60 ~m for metallic powders.

3.0 New Plasma Equipment

Based on the above principles, a number of supersonic plasmatrons with a power of 10-40-80-180 kW and hardware sets were developed for spraying of coatings in the hydrocarbon gas - air combustion products plasma [12,13,14]. These plasmatrons implement a new approach based onformation of the extended slightly under-expanded supersonic plasma jet. A decreased dissipation of the jet power is provided by suppression of turbulence in the boundary layer. This is achieved through using fine effects of dynamics of the plasma. Main peculiarities of behaviour of the molecular gas plasma under non-equilibrium conditions are associated with vibratory-translational non-equilibrium, which can amount to several thousands of degrees. In this situation the possibility exists of reversion of the second viscosity (the second or bulk viscosity becomes negative). This leads to growth of sound generated by natural turbulence, rather than to its attenuation. The efficient reinforcement of sound due to reversion of the second viscosity occurs at frequencies of 10-100 kHz. The intensive sound waves, which are formed and amplified in one region of the flow and absorbed in the other region (downstream), can have a fundamental effect on hydrodynamic parameters of the flow and electrophysical properties of the discharge. Thus generated supersonic plasma jet is characterized by increased (by 30 %) accelerating and heating capabilities. All refractory materials are melted through at a particle velocity of about 600 m/s.

Plasma spraying machines based on the unified modular design:

PLAZER-40

Plasma spraying machine: includes plasmatron with a power of 40 kW; can be made as manual or mechanized modifications; is designed for application of coatings to outside and surfaces; is intended for powder and wire spraying. The plasmatron is made with one interelectrode insert and recuperative cooling, can operate in sub- and supersonic modes. The plasma gas is air + methane. The machine consists of power supply, control panel, powder feeder, plasmatron and service lines.

Mains voltage		3 x 380 V
Open circuit voltage		180 V
Operating voltage		140-180 V
Operating current		100-250 A
Flow rate of the gas mixture		3 - 10 m^3/h
Efficiency of the plasmatron		90 %
Deposition efficiency:	metals	10 kg/h
	ceramics (AL_2O_3)	5 kg/h

PLAZER-80

Plasma spraying machine: includes plasmatron with a power of 80 kW; features separate (or combined - at a Customer's request) feed of gases; is made as mechanized modification; is intended for operation as part of automated and mechanized systems; can be fitted with a unit for independent cooling. The plasma gas is air + methane (propane-butane).

Mains voltage		3 x 380 V
Open circuit voltage		300 V
Operating voltage		200-270 V
Operating current		100-300 A
Efficiency of the plasmatron		70 %
Deposition efficiency:	metals	25 kg/h
	ceramics (AL_2O_3)	10 kg/h

PLAZER-180

Plasma spraying machine: includes plasmatron with a power of 180 kW [15]; is made as mechanized modification; can operate in sub- and supersonic modes; is intended for operation as part of automated and mechanized systems; can be used in all cases where it is required to produce high-quality coatings at high productivity. The plasma gas ia air + methane.

Mains voltage		3 x 380 V
Operating voltage		250-450 V
Operating current		200-400 A
Flow rate of the gas mixture		10 - 30 m^3/h
Efficiency of the plasmatron		70 %
Deposition efficiency:	metals	50 kg/h
	ceramics (AL_2O_3)	15 kg/h

4.0 Conclusions

1. Plasma-forming environments include the readily available high-enthalpy reactive air-gas plasma, which is widely used for technology purposes. Theoretical principles of building the high-efficiency equipment and developing processes that use it are described.

2. Hydrocarbon gases added to the plasma gas lead to substantial quantitative and qualitative changes in properties of the stabilized electric arc, characteristics of the plasmatrons and the generated plasma jet, as well as conditions of thermal and gas-dynamic interaction of the jet with the material treated.

3. The slightly under-expanded supersonic jet flowing out from the sound nozzle is the jet of choice for plasma spraying.

4. The processes occurring in the near-electrode region at the thermochemical cathode of the arc burning in the air-gas mixture are described. Conditions for long-time existence of the discharge in the combustion products plasma at a drastic contraction of the arc at the cathode were established as a result of theoretical analysis and experimental studies.

5. The new approach to building the increased-capacity plasma spraying equipment was developed. It is based on the use of the plasmatrons with a single inter-electrode insert extended to 10 gauge lengths. In such a plasmatron the increase in power is achieved by increasing the arc voltage at a limited value of the electric current.

6. Technology peculiarities of the process of spraying in the combustion products plasma and properties of the coatings of different materials are described. It is shown that a radical method for improvement of service properties of thermal spray coatings is transition to supersonic velocities.

7. The new types of plasma equipment were developed and the new processes were applied.

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6.0 References

1. Deich M.E. “Technical gasdynamics”. Moskow, Energy, 1974, 552p.
2. Lukianov G.A. “Supersonic plasma streams”. Leningrad, Machinostroenie, 1985, 264p.
3. Cowley M.D. and Chan S.K. “Integral method of analysing electric arcs”. *J.Phys.D.: Appl.Phys.*7, 1974, 2232-2245p.
4. Zhukov M.A., Koroteev A.S., Uryukov B.A. “Prikladnaya dinamica termicheskoy plasmy”. Moskow, Nauka, 1975, 298p.
5. . Petrov S.V., Karp I.N. “Plasma Gas Air Spraying”, Kiev. Naukova dumka, 1993, 495.
6. Saffman P.G. “The lift on a small sphere in a slow shear flow”. *J.Fluid Tech.*,22, №2, 1965, 385-400 p.
7. Karp I.N., Petrov S.V. “High - efficiency Combustion Product Plasma Spraying” *Proceedings of the 12 th International Conference Thermal Spraying.* London, UK, 4-9 June 1989, V2, 72.1-72.9 p.
8. Borisov Yu.S., Petrov S.V. “Using of the Supersonic Jet in Thermal Spraying Technology” *Avtomaticheskaya Svarka,* **7**, 1995, 41-44 p.
9. Karp I.N., Petrov S.V., Paschenko V.N. ‘New Plasma Spray Apparatus’ *Proceedings 1994 National Thermal Spray Conference.* Boston, Mass. 20-24 June 1994, 240-245p/
10. Borisova A.L., Borisov Yu.S., Petrov S.V., Novak P. “Structure and Properties of

Coatings by Supersonic Air Gas Plasma Spraying” *Proceedings of the 14 th International Thermal Spray Conference*. Kobe, Japan,22-26 May 1995, 211-216 p.

11. Petrov S.V., Saakov A.G. “Fundamentals of Combustion Products Plasma - Surface and Particle Interaction” *Proceedings of the 14 th International Symposium on Plasma Chemistry.* Prague, Czech Republic.2-6 August,1999, V.4. 2095-2100 p.
12. Petrov S.V. “Technological Usage of Combustion Products Plasma and its Generation” *Ecotechnologies and Resource Saving.* **3,**1999, 73-80 p.
13. Petrov S.V**. “**Plasma synthesis in technology of thermal spraying” *Powder metallurgy,* **9,**1997, 34-38.
14. Petrov S.V., Saakov A.G. . “Novel anticorrosive coating for rust protection of structures”**.** *Proceedings EUROMAT 98*, Lisbon, 22-24 july 1998, - V.3,105-114 p.
15. “Supersonic plasma spraying system (RPE TOPAS)”. EDOXICA REPORT on thermal spraying. **2,** September 1998, 8-9 p.