Analysis of processes in DC arc plasma torches for spraying that use air as plasma forming gas

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Abstract. Developed in Saint Petersburg State Polytechnical University technological processes of air-plasma spraying of wear-resistant, regenerating, hardening and decorative coatings used in number of industrial areas are described. The article contains examples of applications of air plasma spraying of coatings as well as results of mathematical modelling of processes in air plasma torches for spraying.

1. Introduction
Application of DC arc plasma torches for spraying of coating is well known [1–3]. For that purpose they usually use a DC arc plasma torch with a variable arc length in which they use nitrogen, inert gases (argon, helium) and their mixtures with hydrogen as the plasma forming gas [2].

Studies being performed for many years in the Department of Electrical Power Engineering and Equipment of St. Petersburg State Polytechnical University (SPbSPU) were a basis for a development of DC arc plasma torches for spraying that have the following main features: a design is based on an interelectrode insert and an application of air as plasma forming gas. There were developed a large number of plasma spraying technologies for various purposes (heat-resistant coating, wear-resistant one, corrosion-resistant one, protective one, decorative one, etc.) using such plasma torches [3, 4].
The article presents examples of application of used plasma equipment as well as an analysis of processes in the DC arc plasma torch for spraying using a mathematical modelling.

2. Examples of applications
Department of Electrical Power Engineering and Equipment of Saint Petersburg State Polytechnical University and Science and Educational Technological Centre “Electrotechnology” perform theoretical and experimental researches in the area of plasma techniques and technology over 50 years [3].

As a result of performed researches there were developed plasma torches and realized technologies of spraying of different protective coatings on new manufactured parts and technologies of recovery of out-of-repair items [4]. There were realized technologies of recovery of out-of-repair parts of industrial machines (spindles, seats for bearings), plain bearings of turbocharging compressor shafts for internal-combustion engines as well as technologies of air-plasma spraying of wear-resistant coatings on automotive crankshaft journal (freezer compressor) [4].
Fig. 1 shows the process of plasma spraying of aluminium coatings onto carbon fiber to improve the properties of supercapacitors [5].
There were developed technologies of surface hardening of stop equipment of gas main lines. There were worked through conditions of spraying of wear-resistant and corrosion-resistant coatings on surfaces of plungers of autocrane elevators, face seals and rods of water pumps. Air-plasma spraying provides to create coatings from metals that are usually exposed to considerable oxidation, for example, copper coating [4]. Fig. 2 presents parts of gas turbine GTN-25 with a heat-shielding zirconium dioxide coating created by air-plasma spraying.

Modern industry requires increasing of energetic branches, particularly in oil industry and power production. One of the problems, which were solved with air-plasma spraying, was a problem of wearing of threaded connection of pump-compressor pipes that used in oil industry. That problem was very important because during operations the threaded connection of pipe breaks down in the first place. Coatings were created from powder materials of different compositions with size of particles less than 50 µm. Optimal conditions of spraying were determined versus variation of following operational conditions: arc current, arc voltage, plasma forming air flow rate, spraying distance, torch velocity relative to pipe, angle between particles flow and pipe axis [6, 7]. Example of pipes with threaded connection that was hardening by coatings were exposed to wear-resistant tests using a stand imitating pipe screwing. Coating wear-resistance as well as pipe breaking strength in an area of the threaded connection was estimated. Results of tests have shown that a wear
resistance of thread with coating is increased in several times in comparison with an initial version without coating.

A new important trend is a coating for restoring of metal sculptures and monuments. In St. Petersburg, as in other historical centres of the world, there are a lot of monuments which have different damages because of aggressive influence of city’s atmosphere.

There was elaborated an air-plasma technology of corrosion-resistant and decorative coatings for copper alloys. A preoxidised copper powder was chosen as a coating material. Previously, it was investigated a level of powder’s oxidation and regimes of the spraying. One can choose the colour of the coating by varying the level of powder’s preliminary oxidation (see. Fig. 3) [8].

Total technology of coatings includes several stages [9]:
- stream-vortex cleaning of surface;
- air-plasma spraying;
- impregnation an inhibitor of corrosion into the coating’s porosity;
- surface treatment with natural wax.

Preliminary test was realized on bronze, brass and copper plates with size 150×150 mm. Thickness of the formed coatings was about 100 µm. The covering samples were processed by solution of inhibitor and fitted for test in climatic camera. As a result based on accelerated test on corrosion stability it was determined an optimum regime of the air-plasma spraying. Test in climatic camera have shown that such covering can stand more than 70 years in our climatic condition without any trace of the corrosion.

The elaborated technology was used on practice in Saint Petersburg during last restorations of sculptures group “Tamer of horses” by P. Klodt (the Anichkov bridge), metal parts of “Aleksander’s column” (the Palace square) and of sculptures group on the Senate and Synod Building (see Fig. 4).

There is a possibility of applying of such covering not only for restoring purposes but as anti-corrosion covering in different branches of industry.

3. Mathematical modelling

In conditions of widespread applications of air-plasma spraying it is very important to know the qualitative and quantitative relationship between technological efficiency of the spraying process, on
the one hand, and the geometry of the plasma torch and its mode of operation (arc current, gas flow rate etc.) on the other hand. An effective way of obtaining this information is the mathematical modelling of plasma processes in the arc plasma torch for spraying.

Used mathematical model of plasma processes in the arc plasma torch for spraying is based on the following assumptions: plasma is in the state of local thermodynamic equilibrium; plasma is laminar and optically thin. Those assumptions let us to consider plasma as a continuous medium. Equations included in the model express fundamental conservation laws (energy, momentum, mass) and are given in [10]. The region inside the plasma torch and a region of plasma jet were taken as the computational domain as can be seen in Figs. 5 and 6.

Plasma properties are also included in the mathematical model. Their dependencies on temperature (typically at atmospheric pressure) are given in the literature for main gases used in arc plasma torches for spraying, for example in [11].

A series of calculations of plasma processes in the air-plasma DC arc plasma torch PN-V1 was carried out with the following operational parameters: the arc current was varied between 150 and 200 A, the gas flow rate was varied between 0.6 and 1.2 g/s. Distributions of plasma temperature, velocity, pressure and electromagnetic functions were obtained as results of calculations. Examples of obtained distributions of plasma temperature and axial velocity are presented in Fig. 5 and 6.

Comparing the results of calculations one can draw the following conclusions:
- temperature at the outlet of the plasma torch increases when the arc current increases (at a constant flow of gas) and when the gas flow rate increases (at a constant arc current);
- velocity at the outlet of the plasma torch (1256 m / sec) at the arc current of 200 A and the gas flow rate of 1.2 g/s is higher than for other operational conditions. Comparing the results at the same arc current one can see that the plasma velocity depends on the gas flow rate namely the plasma velocity is higher when the gas flow rate is higher.
4. Conclusion

It was shown that an application of air as the plasma forming gas in plasma torches for spraying has certain advantages in a number of cases. These include not only the low cost and high availability of air as the plasma forming gas but also an ability to control the properties of the sprayed coating, namely, the degree of oxidation.

Developed equipment, techniques of experimental investigations, mathematical models of plasma processes and results of investigations are the basis for the implementation of the technology of air-plasma spraying of wear-resistant, corrosion-resistant, recovering and thermal barrier coatings as well as of protective and decorative coatings on the monuments of different materials.

References

[1] Pfender E., 1999 Thermal plasma technology: where do we stand and where are we going? Plasma Chem. Plasma Process 19 1.
[2] Fauchais P. 2004 Understanding plasma spraying J. Phys. D: Appl. Phys. 37 9 R86.
[3] Frolov V. Ya., Klubnikin V. S., Petrov G. K., Yushin B. A. 2008 Technique and technology of coatings (St. Petersburg Polytechnical Univ., in Russian).
[4] Frolov V., Petrov G., Yushin B., Dubov M., Charkin I., Ivanov D. 2009 Research and development of plasma technologies of spraying of coatings Proc. 18th Symposium on Physics of Switching Arc (Nové Město na Moravě, Czech Republic, Sept. 7.-11., 2009) eds V.Aubrecht, M.Bartlova pp 162–165.
[5] Isaeva E.M. 2014 Investigation of the process of plasma spraying of aluminum coating onto the carbon fiber: Master Thesis (SPbSPU, St. Petersburg, in Russian).
[6] Petrov G.K. et al. 2006 Equipment and technology of spraying of air plasma coatings: basic scientific and technical results and achievements SPbSTU Proceedings 501 pp 139-130 (in Russian).
[7] Baeva M., Zalath J., Petrov G., Ushin B., Ivanov D., Frolov V., Uhrlandt D. 2011 Study of plasma torches used for air plasma spraying of protective and decorative coatings Proc. XIXth Symposium on Physics of Switching Arc (Nové Město na Moravě, Czech Republic, Sept. 5.-9., 2011) eds V.Aubrecht, M.Bartlova pp 105–108.
[8] Ushin B.A. 2010 Development of air-plasma technology of spraying of protective and decorative coatings: PhD Thesis (SPbSPU, St. Petersburg)
[9] Petrov G.K., Frolov V.Ya., Ushin B.A. 2013 Method of forming of protective and decorative coating on a metal surface RF Patent 2486276, filed February 29, 2012, and issued June 27, 2013.

[10] Dresvin S.V., Ivanov D.V., Frolov V.Ya. 2012 Method of calculation of thermal plasma processes Induction heating 4(22) 25 (in Russian).

[11] Boulos M. I., Fauchais P., Pfender E. 1994 Thermal Plasmas: Fundamentals and Applications, Vol. 1 (New York: Plenum Press)