АВАЦІЙНА ХІММОТОЛОГІЯ

УДК 621.793.7.001.5

INVESTIGATION OF PROPERTIES OF COATINGS DEPOSITED BY DIFFERENT ARC SPRAYING METHODS

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The results of comparative analysis for properties of coatings deposited by an electric arc spraying (EAS) using gas-air mixture and an activated electric arc spraying (AAS) using the products of combustion of propane-air mixture. Under optimal spraying process conditions, the porosity of AAS-produced coatings is much smaller as compared to EAM: 2–4 % and 9–11 %, respectively. The adhesion strength of AAS coatings is higher by 1.8–2.2 times. When developing techniques for the base roughness decrease, it is necessary to choose those techniques for pretreatment of base surfaces which provide low roughness Rz: within 5–10 mcm.

Keywords: electric arc spraying, coating, adhesion strength, roughness.

Подано результати порівняльного аналізу властивостей покриттів нанесених традиційним електродуговим напиленням (ЕДН) — що використовує для розпилювання газ-повітря, і активованим електродуговим напиленням (АДН) — яке для розпилювання використовує продукти згоряння пропано-воздушной суміші. За оптимальної технології напилення пористість покриттів, отриманних за методом АДН, значно менша, ніж при традиційному ЕДН (2–4 % і 9–11 %, відповідно). Міцність зчеплення покриттів, що наносяться активованим електродуговим напиленням, вище в 1,8–2,2 рази. При розробці технологічного процесу напилення для зниження ступеня шорсткості деталі необхідно вибирати методи попередньої підготовки поверхонь, що забезпечують низький ступінь її шорсткості: Rz від 5 до 10 мкм.

Ключові слова: електродугове напилення, покриття, міцність зчеплення, шорсткість.

Introduction

The development of up-to-date transport is tightly coupled with the problem of the longevity of its parts. Cam- and crank-shafts are the most responsible and expensive engine parts. During operation, alternative loads on the shaft promote the following phenomena:

– friction and wear of its necks;

– fatigue failures in the neck-to-web passages and at the oil channel outlets;

– bending and twisting owing to its bending, torsion and axial vibrations [1; 2].

The shaft neck — bearing coupling operates under conditions of hydrodynamic lubrication. However, the stability of conditions of hydrodynamic friction is frequently broken, and semiliquid and sometimes semidry friction arise, for example, at the start moment or other short-time overloading of the engine. Under such conditions, the wear rate of shaft and bearing surfaces increases [1; 2]. However, the behavior of shaft, the webs of which have been recovered via deposition of a coating, is different. Pores in a coating are filled with the oil which flows out of pores due to the shaft rotation. The oil immediately forms a protective film located around the shaft neck. Moreover, resulted from abrasion metallic particles are pressed into pores moving away from the friction region.

Techniques for prolongation of the service life of crankshafts, which are the most expensive parts of transport means, have been studied well enough and are still being improved. As a rule, inserts and bushes, which form triboconjuctions with crankshafts, wear sooner. In most cases, they are not renewed and instead replaced with new ones.

Traditionally, the working layers of inserts and bushes are made from low-friction materials on the basis of copper, tin, aluminum and their alloys. Herein scarce and expensive nonferrous metal is spent uneconomically.

Increase in the service life and reduction in expenses for manufacture and maintenance of friction pair parts (crankshafts, inserts, bushes et al.) of transport machinery is one of the most important problems to be solved by scientific researchers, technologists and constructors.

The carried out researches and experimental works have shown that one of the most efficient ways to the solution of this problem is the use of electric arc spraying (EAS) for deposition of coatings. In the 80th, there were created workshops for production of parts with plasma, detonation and arc coatings. However, in the 90th implementation of them into machinery practically stopped owing to the changes in the Ukrainian economy. The constant lack of certain spare parts has become an urgent problem of transport means. The development of international cooperation leads to continuous rise in application of transport means produced abroad, whose maintenance requires steady increase in the quantity of various spare parts. The achievement of these purposes requires hard currency, which is a difficult enough problem. Under the conditions of the broken economic ties and increasing international cooperation, the development of modern technologies for strengthening and protection of new parts against corrosion and renewal of worn ones will make it possible to improve the reliability and longevity of transport means as well as to significantly weaken the dependence on foreign providers of important expensive metal-consuming scarce parts. Herein selection of techniques for strengthening, corrosion protection and reconstruction of parts, which must provide ecologically conscious production, long service life of parts and be universal enough, simple and available, is of great importance. Methods for plasma and detonation spraying, which have been counted on in prolongation of the service life of parts for transport means, require bigger expenses because of expensive equipment and gases. In the current world engineering which deals with the development and application of techniques for deposition of protective coatings and renewal of parts using thermal spraying, more and more attention is paid to electric arc spraying. Nowadays this method is widely applied, especially in the European countries and steadily replays the traditional gas flame method thanks to many advantages as follows [3–5]:

– the required equipment is produced in SNG countries and is simple and cheap;

– the developed equipment for EAS permits deposition of coatings, the quality of which does not yield coatings obtained by plasma and denotation methods;

– increased thermal effectiveness up to 57 % as compared to 13 and 17 % for gas flame and plasma spraying, respectively;

– high efficiency, which is 3–4 times higher than that for gas flame spraying;

– the absence of need in scare gases;

– availability of power sources for metal melting;

– possibilities of mechanization and automation;

– manufacture of better coatings with higher adhesion strength as compared to gas flame spraying.

The tendency to replace a gas flame rod spraying with EAS has appeared lately.

However in the beginning, EAS was only aimed at corrosion protection of welded metallic constructions, and properties of electric arc coatings for other purposes have not been studied properly yet. Therefore implementation in industry of EAS in order to prolong the service life of parts and renew them for provision of transport enterprises with spare parts is an actual task.

The purpose of the work was to investigate properties of EAS-derived coatings designed for prolongation of the service life and renewal of friction pair parts (crankshafts, inserts, bushes et al.) of transport machinery.

Investigation of physicomechanical properties of EAS coatings

The main physicomechanical properties of EAS coatings affecting their operation characteristics are the adhesion strength and porosity. For comparison of the quality of coatings deposited by different EAS techniques, the authors have investigated physicomechanical properties of coating samples made from steel 12Kh18N9T using an activated arc spraying on a unit ADS-8 of the OIM NAN “Belarus” as well as on an apparatus for EAS DM-2 with EM-14M unit, produced at the Barnaul mechanical plant [6; 7]. As a result of the conducted experiments, the dependences of the adhesion strength, porosity and gas permeability of coatings on the spraying process parameters such as the current and voltage of arc, spraying distance, speed of spraying apparatus movement relative to the base surface, pressure of the compressed air or combustion products in the distributor head of the electric arc apparatus as well as on the surface pretreatment have been established. The base surface was prepared for spraying using bead blasting treatment. The roughness of the prepared surface (R_z) fell in the range 5–60 mcm.

Before spraying samples were fixed in a special device located in the holder of the lathe. Arc spraying apparatuses were placed on the support of the lathe. The speed of the apparatus movement relative to the sample surface and the spraying distance could be governed by varying the revolution number of the spindle and the support-spindle distance.

The AAS unit was a modern universal system which combined advantages of electric arc and high-rate spraying. Its chief distinctive feature is the presence of a small high-efficiency chamber for combustion of propane-air mixture, whose ultrasonic jet left the chamber with a speed of 1500 m/s at 2200 K. The flow strength, determined by the ratio of the kinetic energy to the gas volume and characterizing the force acting on a particle in the flow, was equal to 75 kPa for traditional arc spraying and to 234 kPa for AAS apparatuses. The latter permitted melted metal particles to speed up to 500 m/s and to form a coating with doubled adhesion strength compared to traditional arc spraying and sufficient for operation under extreme conditions including the presence of shock-abrasion wear. The use of the products of propane-air mixture combustion as a spraying gas significantly decreased oxidation of sprayed metal and burning-out of alloying elements. For example, at the fuel combustion coefficient K = 0.4 the carbon amount in the coating made from 40Kh13 and 12Kh18N9T rods practically did not differ from that in the initial rod. However at equal amounts of air and propane the carbon content in coating was lower than that in the initial material by two times, whereas in spraying by pure air (traditional EAS) the carbon content decreased by three times. The conditions of formation and transport of particles as well as of coating formation, which differ from other methods, lead to formation of different structures in the coating material. The small amount of brittle oxides, high content of intermetallic compounds along with formation of hardening structures and high enough plasticity of the deposited layer create favorable background for application of this method for strengthening and renovation of parts of transport means and essentially widen the nomenclature of parts that can be renewed. Moreover, under high-rate spraying conditions, the coefficient of material concentration in the jet increases as the divergence angle of two-phase supersonic jet is smaller as compared to undersonic jets and is equal to 5–7°. As a result, the diameter of deposited spot decreases and the coefficient of material consumption increases. For AAS it reaches 0.85 against 0.75 for traditional EAS. As a material for spraying, a wire from any commercial material (zinc, aluminum, copper, brass, bronze, nichrome, carbon and stainless steels, etc.) can be used as well as a powdered wire or combination of any two wires. The porosity of steel coatings is within 2–4 %; density of aluminum wires is close to that of cast material. This factor is particularly important in production of anticorrosion coatings as herein significant saving of spraying material is attained at the expense of decrease in the coating thickness required for closing of through porosity, and thus the service life of coatings increases.

For spraying, 2.0 mm 12Kh18N9T wires (GOST 5632-72) were used. The process conditions were as follows: arc voltage 32 V, spraying distance 50–200 mm, arc current 100–400 A, compressed air consumption 80 m^3/h, pressure 0.65 MPa; when the apparatus ADM-8 was used, propane-butane consumption was 0.011 kg/h, pressure 0.4 MPa.

The porosity of coatings was determined via hydrostatic weighing according to GOST 18893-73. In order to study distribution of pores through a coating and to determine their size and shape, the system of texture analysis of images Leitz TAS (Germany) was used composed of a microscope “Ortoplan” with a TV camera, a unit for processing of TV signals and a display. The system operates under the control of a computer designed on the basis of microprocessor LS1–II/2. To examine coatings, metallographic samples were prepared according to the standard techniques [8]. To determine gas permeability of coatings from steel 12Kh18N9T, samples were made in the form of a bush with a hole and a conic end pin from steel 20. Before spraying, the end surface of the tin was subjected to jet-abrasion treatment for modeling of surface roughness followed by heating in air to 700–760 K for 3–5 min. In such a way, a thick oxide film was formed which prevent from the evolution of chemical interaction between the materials of coating and base. The pin was inserted into the bush, and spraying started to the achievement of required thickness of coating. Then the pin was carefully separated from the coating and taken out the bush hole. The coated sample was put into a unit for measurement of gas permeability. The coating thickness was measured with a micrometer; the area was determined on the basis of the bush hole before spraying. The adhesion coating-part strength was estimated using a glue method [8]. Metallographic examination was performed on an optic microscope MIM — 8 with the magnification 90-200 and a SEM microscope “MSV-2” (firm “Akasi”) with the magnifications 100 and 200. Samples for metallography were prepared using standard techniques [8]. Roughness of the surfaces of base and coating was estimated on a profilograph-profiler of type 201.

The analysis of the structure of coatings produced using EAS and AAS revealed that the latter provides particle sizes which are 5–6 times smaller compared to traditional spraying. Consequently, the sizes and quantity of pores in AAS coatings decreased by 2–3 times.

Gas permeability is a structure-sensitive characteristic of coating, and there is a distinct enough dependence of it on open porosity [8; 9]. Under optimal spraying conditions, the porosity of EAS coatings is much lower than in the case of liquid metal spraying with cold air (2–4 % and 9–11 %, respectively), and the gas permeability is lower by approximately 30–40 times. This may be related to the essential decrease in the sizes of pore channels in coatings. Fig. 1 demonstrates the curves of pore size distribution for AAS and EAS coatings. The analysis showed that for AAS the number of pores is much smaller. Herein the minimal porosity and gas permeability are attained at spraying distances within 50–60 mm.

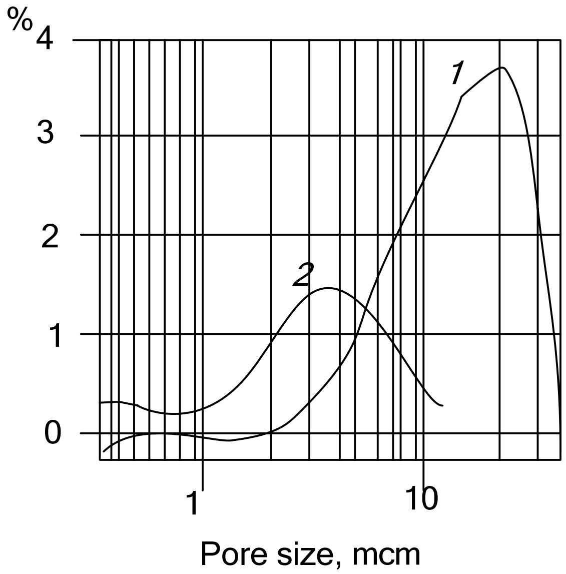

Fig. 1. Pore size distribution:
(*1*) traditional EAS; (*2*) activated EAS

In case of high-efficiency spraying, that is, at currents of 400 A and higher, high enough apparatus movement speed (relative to the base) is required. There was observed different dependences of the porosity (*P*) on the spraying distance (L_s) for AAS and EAS coatings. The porosity of AAS coatings obtained at the minimal apparatus speed, that is, after a one-run deposition, decreased with shortening the spraying distance to 100 mm, but then it increases to the values characteristic for EAS coatings. The speed increase results in decreasing porosity in coatings obtained at small distances ($L_s < 80–90$ mm). Slight decrease in porosity is observed in EAS coatings as well. The weak effect of the spraying apparatus speed on the coating porosity at distances $L_s > 80–90$ mm is caused by weakening of the aerodynamic effect of the reflected plane jet and cooling of $d_p < 1$ mcm particles to temperatures, at which they do not adhere onto base asperities.

The peculiarities of the effect of the arc current (I_a) on the coating porosity are worth noticing. Whereas at big arc currents an increase in the spraying apparatus speed (V_M) markedly decreases porosity, spraying at small currents practically does not affect it. This may be prescribed to small both spraying efficiency and mass-average particle temperature at small arc currents [9]..

Properties of anticorrosion electric arc coatings depend on not only the value but also the type of porosity.

The authors [8; 9] have proposed to divide porosity into a volume and a surface one as at a layer thickness commensurable with the average microasperity height a drastic change in porosity occurs, which, in its turn, is accompanied by a drastic change in structure-sensitive characteristics of coating, for example, gas permeability.

The investigation of the effect of the thickness of coating on its porosity has shown that the AAS method provides a decrease in the porosity (Fig. 2, *a*). The profilographs indicate the fact of decrease in the surface roughness of a AAS-derived coating. The average microasperity height of the 0.1 mm thick steel coating deposited on a polished base surface at a spraying distance of 100 mm was 5–10 and 30–50 mcm for AAS and EAS, respectively. The reduction in surface roughness of the AAS coating is connected with the particle size decrease and may be the main reason for lower coating open porosity at small thicknesses due to decrease in the surface component of porosity due to bigger surface roughness. Such a marked decrease in the AAS coating porosity (for example, at a coating thickness of 0.05 mm the porosity of coatings under the comparison differ by almost an order of magnitude (Fig. 2, *a*) inevitably causes still greater difference in the gas permeability (Fig. 2, *b*). For EAS, reduction in the coating thickness, $h < 0.1$ mm, leads to rapid decrease in the gas permeability. Similar picture is observed in case of AAS, but only beginning with $h = 0.05$ mm.

The sharp rise in the gas permeability may be related to the appearance of a through porosity [9]. Hence, the gas permeability of steel coatings made using the AAS method is lower than that of EAS coatings by 1–2 orders of magnitude. At $h = 0.05–0.1$ mm this difference reaches 4–5 orders of magnitude.

To reach required adhesion strength, which is determined by mechanical or physicochemical bonds depending on the materials of the “coating-base” pair [8; 9], the base surface pretreatment is conducted. The most used technique is jet-abrasive treatment, which purifies the surface and destroys its equilibrium state with the medium by release of interaction forces of surface atoms, that is, chemically activates the base.

Unfortunately, the base activity rapidly decreases because of chemical adsorption of air gases and oxidation. It is therefore desirable to shorten the time between the pretreatment and spraying as much as possible.

The pretreatment makes the surface rough, which raises the temperature in the contact zone under sprayed particles on microasperities and increases the total surface of spots for welding. The area of a rough surface is larger than that of a smooth surface, which also results in adhesion strength increasing. The rise of R_z is accompanied with increase in the adhesion coating-base strength (σ_{ad}) (Fig. 3, *a*).

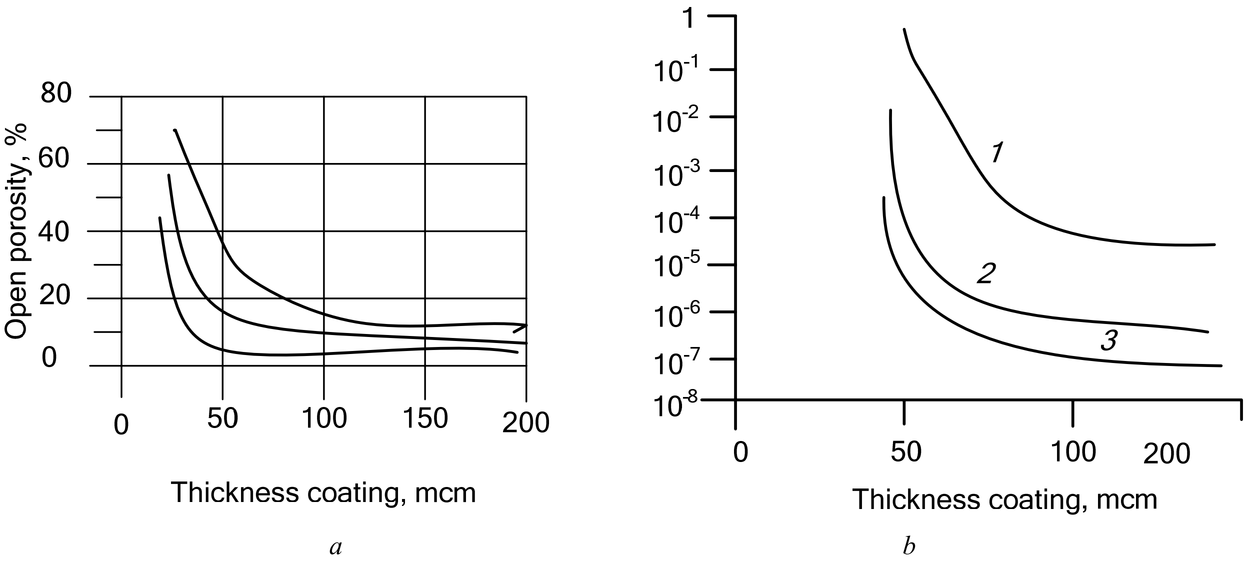

Fig. 2. The effect of the coating thickness on (*a*) the open porosity and (*b*) gas permeability: (1) EAS; (2, 3) AAS at a coating thickness of (1, 3) 100 mm and (2) 50 mm

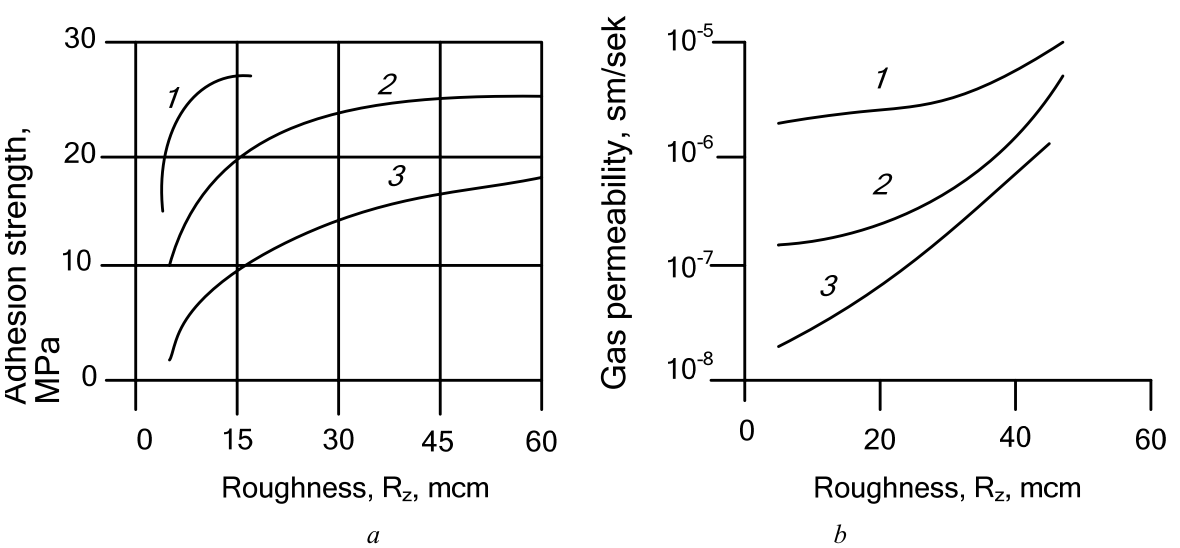

Fig. 3. The effect of the base roughness on (*a*) the adhesion strength and (*b*) gas permeability of (1) traditional EAS and (2, 3) activated EAS at a spraying distance of (1, 3) 100 mm and (2) 50 mm

However, it is not high enough as could be expected taking into account the high particle velocity, which reaches 500 m/s. This may be related to the action of the following main factors:

• increase in the particle velocity increases the relative area of the physical particle-base contact [4], which leads to an increase in the adhesion strength;

• reduction in the average particle size in AAS by 4–7 times reduces the particle crystallization time, lowers both the particle-base contact temperature and completeness of chemical interaction, which can reduce the adhesion strength.

Thanks to the action of these factors, the adhesion strength of AAS coatings is higher by 1.8–2.2 times.

However, in manufacture of anticorrosion coatings, whose thickness is usually small (0.04–0.2 mm), the problem of the right choice of roughness becomes principal as in this case, the layer thickness can be commensurate with the height of microasperity. Insufficient roughness accompanied with big thickness of coating may cause the detachment of coating, whereas a rough surface accompanied with small thickness may become the reason of early corrosion.

As shown in Fig. 3, *b*, with increasing the height of base surface microasperities, the gas permeability (K_b) increases for coatings deposited by any method of arc spraying. However, the most marked effect of R_z on K_b is observed on the coating made using an activated EAS. The different degree of the influence of the base roughness on K_b is due to the bigger particle size in the case of compressed air spraying , when the first layer of coarse particles is jammed into pits between microasperities so that they cannot affect the coating formation process. The stronger dependence of the gas permeability of AAS coating on R_z is the result of significant inclination of this method towards formation of porous “bumps”. Conditions for this become more favorable with increasing the base roughness. It should be mentioned that in case of EAS with increasing the coating thickness the effect of R_z on K_b is negligible, whereas for AAS coatings with $h < 0.2$ mm, this effect only diminishes depending on the spraying distance.

Hence, as it was before shown, for coatings produced using an activated EAS, a decrease in the base roughness can lead to significant reduction in their gas permeability. This should be taken into account in the development of spraying process conditions and selection of those techniques for surface pretreatment that provide a low degree of roughness, for example, blowing with quartz sand. Herein the adhesion strength decreases as well, and at low R_z in EAS coatings the adhesion strength required for the impossibility of coating detachment may not be reached, whereas in AAS the adhesion strength is high enough even in case of using a polished base surface.

Approbation of the research results

AAS was used for i)renewal of worn steel cylinder parts operating under conditions of sliding friction and lubrication and ii) elimination of defects and protection against metal corrosion of tubes, internal and external surfaces of reservoirs and multiaimed welded constructions as well as various decorations using spraying with aluminum, zinc and cadmium [8]. In addition, covering of about 50 % surface of each neck is performed under conditions of strong support of the gas flow, as the crankshaft webs forms semi-closed space. The difference in the coating formation conditions causes difference in the physicomechanical characteristics of the deposited layers on different neck spots and so their different wear. The use of AAS which includes mechanical activation of coating in the course of spraying process allows one to equalize the properties of coating along its width and depth.

Crankshaft necks with coatings may be re-polished in the course of the next overhaul for the required size. This is not, however, reasonable as during hard and long operation the wear resistance of the coating decreases due to filling of its pores with the wear products and other impurities. It is more reasonable to remove the old coating and deposit a new one.

AAS has renewed the sizes of support webs of engine camshafts. The results of the operation testing of cam- and crankshafts with using AAS process have demonstrated that the service life of these parts is 1.5–2 times longer as compared to parts renewed using traditional EAS method.

Conclusions

1. Comparative analysis of coating properties has revealed that via using optimal spraying conditions, the porosity of AAS-derived coatings is significantly smaller than that for EAS coatings (2–4 % and 9–11 %, respectively), and at a coating thickness of 0.05–0.1 mm the difference reaches 2–5 orders of magnitude. The adhesion strength of AAS- coatings is 1.8–2.2 times higher.

2. When developing the AAS process for deposition of coatings, one should choose those techniques for pretreatment of the base surface which can provide reduction in the degree of its roughness (from 5 to 10 mcm) required for decreasing its gas permeability and thus porosity.

3. As a spraying gas, AAS uses the products of combustion of propane-air mixture, varying of which makes it possible to form a neutral or a reducing medium in the zone of electric wire melting, and in such a way:

– to decrease metal oxidation and burning-out of alloying elements;

– to increase the strength and wear resistance of coatings and so to prolong the service life of transport means parts.

4. Using the AAS technology, including mechanical activation of coating in the course of spraying, permits equalization of the properties of a coating along its thickness and width.

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Стаття надійшла до редакції 12.09.2013