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Investigation of Upgraded Technology for Plasma Spraying of Bronze Powder Using the Combined Process with Hydrocarbon Additions

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Abstract. The object of the research is thermal spray process for the formation of metal coating from bronze powder in plasma-fuel variant, using direct current (DC) electric arc plasma torch, on steel samples. The aim of the work was to investigate and develop the technology for plasma-fuel spraying of functional coatings (for wear-resistant and antimicrobial applications) on machine-building and medical purpose pieces with increased process capacity and moderate energy consumptions in a comparison with conventional thermal spray technologies with use of inert and oxygen-free gas media. During the study, using experimental and thermodynamic estimation methods, the thermal and chemical parameters of the process under the spraying conditions at ambient pressure were characterized, which made it possible to determine the area of preferred regimes of the developed technology. On the modernized testing unit for plasma spraying of metal powders with power of up to 40 kW, operating using a controlled combination of three types of gases – technical nitrogen and propane-butane (LPG) with compressed air, the measurement and optimization of the operating and constructive/assembling parameters of the system for aluminum bronze coating spraying were established. In this case, the experiments were carried out using the designed fuel intensifier, which is joined with the PP-25 arc plasma torch, as well as additional technological equipment (protective shroud). For samples of the resulting coatings with a thickness of 100 to 450 μm from the bronze material, testing of phase composition and some parameters of the resulting coatings on steel products was carried out. Operating capacity of the proposed process reaches 7–15 kg/h for bronze powder when using a moderate power of the torch – up to 35–40 kW and a limited flow rate of hydrocarbon gas (for example, LPG of the SPBT grade) – 0.1–0.35 kg/h. Analysis of the energy efficiency parameters of the developed technology, as well as its calculated technical characteristics, in a comparison with plasma and combined equipment of a similar purpose, showed that it has an advantage in terms of target indicators, in particular, in terms of energy consumption and total energy efficiency of the spraying unit, not less than 20–30 %. This makes it to proceed later to the stage of application of this technology into production based on a new process for the metal coating formation, in particular with antimicrobial properties, with improved energy efficiency of the process.

Keywords: thermal spraying technology, plasma torch, copper alloy, aluminum bronze, alkane-containing additions, liquefied petroleum gas, experimental study, thermodynamic estimation, phase characterization of coating

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Исследование модернизированной технологии плазменного напыления порошка бронзы с использованием комбинированного процесса с добавками углеводородов

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Реферат. Исследование посвящено процессу газотермического формирования покрытия из бронзового порошка в плазменно-топливном варианте с использованием электродугового плазмотрона на стальных образцах. Цель работы – изучение технологии для плазменно-топливного напыления функциональных покрытий (износостойкого и антимикробного применения) на изделия машиностроительного и медицинского назначения с повышенной производительностью процесса и умеренными энергозатратами по сравнению с традиционными методами термического напыления в инертных и бескислородных газовых средах. С помощью экспериментального и термодинамического расчетного методов оценивались тепловые и химические параметры процесса в условиях напыления при атмосферном давлении, что позволило определить область предпочтительных режимов данной технологии. На модернизированной авторами установке плазменного напыления порошков электрической мощностью до 40 кВт, работающей с регулируемым сочетанием технических азота и пропан-бутана, а также воздуха, проведены измерение и оптимизация режимных и конструктивных параметров системы нанесения покрытия из алюминиевой бронзы. Эксперимент осуществлен с использованием разработанного топливного интенсификатора, стыкуемого с дуговым плазмотроном ПП-25, и дополнительной технологической оснастки (защитного кожуха). Для полученных покрытий толщиной от 100 до 450 мкм из промышленного порошка алюминиевой бронзы проведено тестирование фазового состава и некоторых параметров получаемых покрытий на стальных изделиях. Производительность предложенного процесса достигает 7–15 кг/ч по порошку при умеренной мощности плазмотрона до 35–40 кВт и умеренном расходе углеводородного газа (предпочтительно технического пропан-бутана марки СПБТ) 0,1–0,35 кг/ч. Оценка параметров энергоэффективности разработанной технологии и ее расчетных технико-экономических характеристик в сравнении с плазменным и комбинированным оборудованием аналогичного назначения показала, что она имеет преимущество, в частности, по удельным энергозатратам и общему энергетическому КПД аппарата не менее чем на 20–30 %. Это позволяет перейти к стадии последующего внедрения данной технологии в производство на основе нового процесса получения металлопокрытий различного назначения, в том числе с антимикробными свойствами.

Ключевые слова: газотермическая обработка, электродуговые плазмотроны, плазменное напыление, сплавы меди, алюминиевая бронза, углеводородсодержащие алкановые добавки, пропан-бутан, экспериментальное исследование, термодинамическая оценка, фазовый анализ покрытия

Для цитирования: Исследование модернизированной технологии плазменного напыления порошка бронзы с использованием комбинированного процесса с добавками углеводородов / О. Г. Девойно [и др.] // *Наука и техника*. 2023. Т. 22, № 2. С. 103–112. https://doi.org/10.21122/2227-1031-2023-22-2-103-112

Introduction and research tasks

Last years, in the technologies of thermal spraying of coatings, the group of plasma spraying and related electric arc process (at atmospheric pressure – atmospheric plasma spraying (APS) together with electric arc spraying) has a total market share of about 40 % in the leading industrial regions of the world (as an example for the case of USA) (Fig. 1) [1]. One of the important direction to improve existed industrial APS technologies for deposition of modern functional metal and ceramic coatings (used in machinery production, metallurgy, energy, chemical, aviation industries, medical technologies, instrumentation and some other industries) is to optimize the conditions for heat and mass transfer of powder with plasma jet. In particular, this can be done by improving the operation of electric arc plasma torches in terms of their temperature and velocity parameters and the composition of plasma gases in the torches.

According to the world leaders in a field of protective coatings (Oerlikon Metco AG (Switzerland), Praxair Surface Technologies (USA) and others), the most suitable materials for thermal spraying, including plasma methods, are powders (mainly metal and ceramic ones), which are used annually up to 100 kt [2–6].

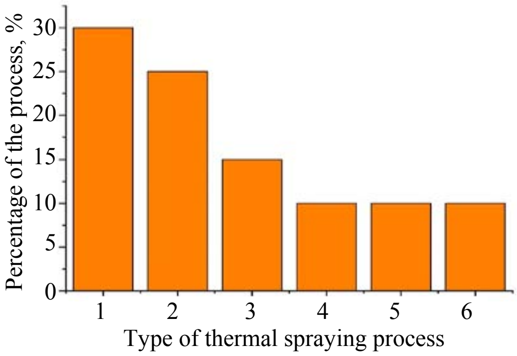


Fig. 1. The current shares in the industrial application of various processes of thermal spraying of coatings in USA according to the data from [1]: 1 – plasma spray; 2 – flame spray; 3 – high velocity oxygen fuel spray; 4 – electric arc spray; 5 – cold spray; 6 – other thermal spray processes

The main disadvantage (along with the limited adhesion strength to the metal base and the complexity of controlling the properties of the formed coatings) that hinders the spread of functional coatings of this type is rather high energy requirement of the process – 3–20 kW·h/kg of the sprayed material and the low powder utilization factor (often it not more than 50 %) during spraying due to its heating and the limited duration of the powder residence time in the zone of the plasma jet with a high temperature [2, 7–8]. Modernization of APS technologies, as a rule, is aimed at eliminating these important technical shortcomings. As part of this important trend in the field of high-temperature coating technologies, over the past decade, a number of countries have been actively developing a group of new APS technologies for a number of ceramic (oxides and carbides) and metal (copper and its alloys for anti-friction and antibacterial coatings, nickel-based alloys, etc.) powder materials. These technologies use both hydrocarbon gases as heat carriers (including plasma mixtures of methane with CO_2) to improve the velocity and thermal conductivity of plasma jets and intensification of particle melting in them, and with feeding of particulates or droplets of organic additives to the plasma jet to control the porosity and microstructure of sprayed metal and composite functional coatings, including for thermally resistant blades of gas turbines (in particular, according to the data [6, 9–14]). At the same time, in recent years, in particular, in Theoretical and Applied Mechanics Institute (Siberian Branch of the Russian Academy of Sciences), an adjacent promising air plasma spraying technology is being developed for use with new medium-power plasma torches to spray powders from a number of alloys, oxides (including doped alumina) and cermet compositions [8, 15–16]. Moreover, as a variant, this technology is proposed for practical use when air as the plasma gas is combined with feeding of additives of alkane hydrocarbons (liquefied gases (LPG) or natural gas) into the plasma torch.

In a connection with the mentioned trends in the field of thermal spraying technologies (in particular, plasma ones), it seems highly promising to develop new processes of this type using the principle of feeding into the heat carrier in apparatus for spraying of metal or refractory oxide powders the inexpensive mixtures (hydrocarbons fuel + + oxidizer) that are effective in terms of their thermophysical properties. This type of plasma-fuel type of spraying is advisable, in our opinion, to focus, in particular, on the use to obtain such relevant functional coatings in recent years as antiseptic and antibacterial coatings based on copper alloys for a number of parts (such as fittings, accessories) in medical institutions. In recent years, plasma-sprayed coatings of this type have already entered the stage of long period testing in several large hospitals in Canada and South America [17]. These coatings can be quite relevant in current period for Belarus under the conditions of increased sanitary and hygienic requirements for medical sector to prevent the expansion of viruses such as COVID-19 or others through special measures to ensure the suppression of so-called “nosocomial infections”.

Based on the above information, as the purpose of this article, we have chosen to investigate the modernized technology of plasma-fuel spraying of metal functional coatings made of aluminum bronze (which is promising, taking into account antimicrobial activity) with increased process productivity and improved energy consumption, due to the introduction of hydrocarbon alkane additives, compared with traditional technologies of plasma spraying in inert and oxygen-free gas environments.

The review on intensification methods for APS with powder materials shows a commitment for use of auxiliary fuel components based on alkanes in spraying systems for formation of metal coatings to decide two tasks:

a) to enhance the energy efficiency of devices of this type (by increasing heating intensity of the powder in the gases with high thermal conduction and active thermal radiation emission), in comparison with arc plasma torches for similar coating deposition, operating both with conventional simple gases (N_2, argon or their mixtures with H_2), and on high-enthalpy hydrocarbon-containing mixtures, which give (during exothermic reactions with oxidizers inside plasma torch channel) combustion products or syngas based on (H_2 + CO)-mixtures;

b) to optimize/variate the chemical composition of the gas flow (by flexible control of oxidation degree of formed gas mixture in a result of fuel addition) when spraying of materials sensitive to other plasma gases during APS, which can lead to undesirable oxidation of metal materials (e. g. in air plasmas used in some supersonic APS units developed recently in the CIS).

Investigation methodology and experimental spraying system

Schematic diagram, which is used for our research experimental system and detailed outline of the fuel injection (mixing with plasma jet) part are shown in Fig. 2–3. Experimental plasma devices, applied in the experiments, use previously recognized and verified methods [2, 5, 18–19].

Initially performed thermal engineering analysis and technical design indicate the prospects for using in the considered variety of atmospheric plasma spray systems with the fuel assistance (FA-APS) such two special parts (preferably without cooling) as vortex chamber (fuel intensifier), which does not use elevated pressure, for the distributed injection of gas fuel components into the plasma jet and the auxiliary tubular channel (shroud). The latter helps to reduce intensity of heat losses (effected by gas convection and radiation) from plasma jet to the ambient air and keep the high jet velocity over a zone of as long as possible [5, 20–21].

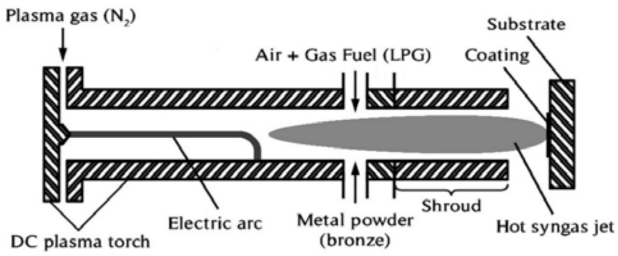


Fig. 2. Schematic diagram of combined system with powder injection, using gas fuel-assisted process for thermal plasma spraying with metal powder feeding to deposit coating on plate steel substrate

Such constructive principle will provide advantages over analogues, in particular, using in FA-APS installations a special cooled chamber for combustion with oxygen oxidizer of auxiliary fuel at increased pressure (0.4–0.5 MPa, see Fig. 4 [22–23]) attached behind the nozzle of arc plasma torch. This significantly limits the efficiency (including thermal efficiency and electrode life period) and complicates the design of direct current (DC) plasma torch, in the discharge channel of which this increased pressure is also transferred. In our preferred variant, more simple arc plasma torches, e. g. of the PP-25 type, conventional for standard industrial spraying units of the UPU-3D type [2, 18], can be efficiently applied.

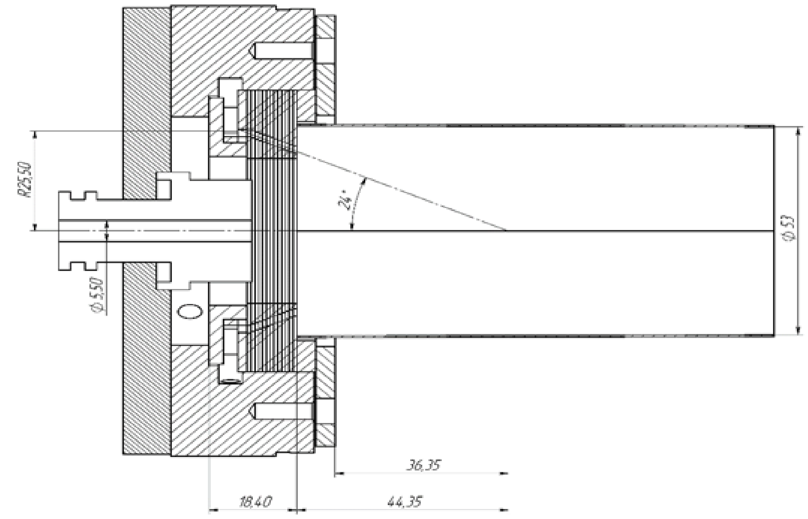


Fig. 3. Outline for the fuel intensifier with input of mixture (air + gas fuel) in the jet of DC arc plasma torch (with gas vortex stabilization of electric arc) for thermal spraying of powders, at an angle to the plasma jet axis

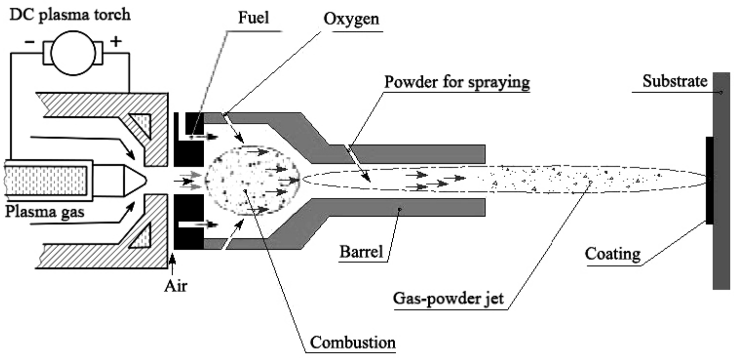


Fig. 4. Schematic of combined experimental plasma-fuel system (atmospheric plasma spraying + high velocity oxygen fuel spray) for high-speed spraying of powders, based on an direct current arc plasma torch in combination with injection chamber for elevated pressure (hydrocarbon fuel + O_2 oxidizer) mixture and with the injection of ceramic or metal powder after the chamber for the spraying deposition of coating [22]

For thermochemical assessment of composition of gaseous and solid phases in investigated experimental system (corresponding to media in FA-APS), the simulation based on analysis for the range T = 300–3000 K with calculations for thermodynamically equilibrium systems at atmospheric pressure, using, in particular, multifunctional TERRA code (designed in Moscow State Technical University, Russia) can be used at the acceptable accuracy [24–25].

Thermochemical estimation for the experimental system conditions

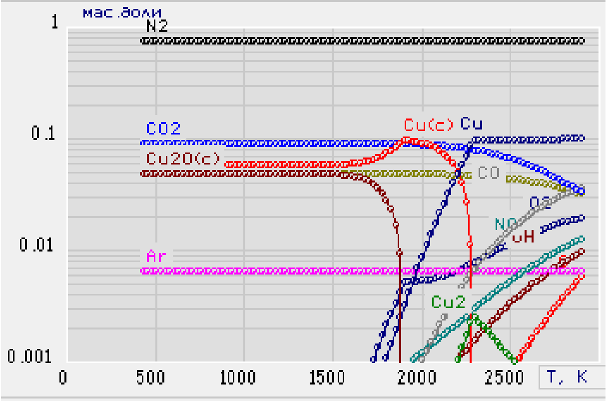
The calculating thermodynamic assessment of the consumption of gaseous fuel components in the proposed powder spraying system (for the case of Cu, Ni and their alloys) has shown that the FA-APS process will have advantages under optimal conditions (compared to the conventional for industry APS technologies), such as:

a) reduced energy consumption for heating and melting of sprayed materials;

b) increased operating capacity of the process (in kilograms of injected powder at a plasma torch power of not higher than 40 kW);

c) the opportunity to control the composition, the oxidizing ability of the gas flow as well as the temperature profile in the zone of powder heating in order to optimize the properties of deposited coatings. This includes protection against air thermal oxidation of sprayed powders (metal or other, e. g. carbide ones), due to their heating in the channel of shroud of FA-APS system in formed non-oxidative ($CO + H_2 + N_2$) mixture.

Figures 5–7 demonstrate the examples of the obtained results at the regimes with different level of the equivalence ratio (ER) [3–4, 6].



p = 1.101 MPa

Fig. 5. Composition (in weight fractions) of equilibrium C–H–O–N–Ar–Cu-system, based on the air + LPG mixture for the conditions of plasma-fuel spraying of copper coating at the value of oxidizer to fuel equivalence ratio ER = 1.05 (complete oxidation gas medium) for T = 400–3000 K, p = 0.1 MPa

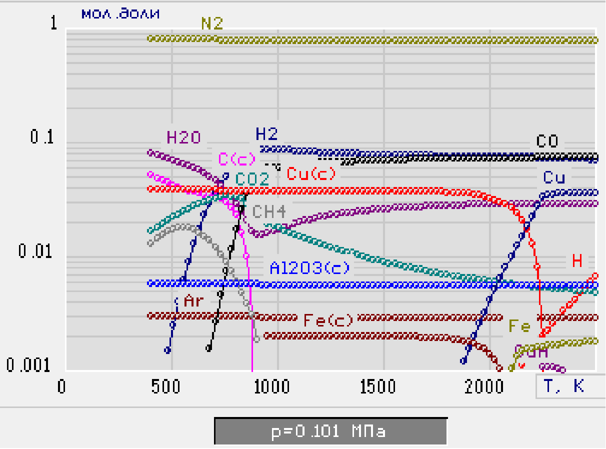


Fig. 6. Composition (in mole fractions) of equilibrium C–H–O–N–Ar–Cu–Al–Fe-system, based on the air + LPG mixture for the conditions of plasma-fuel spraying of bronze coating at the value of ER = 0.50 (partial oxidation gas medium) for T =400–2500 K, p = 0.1 MPa

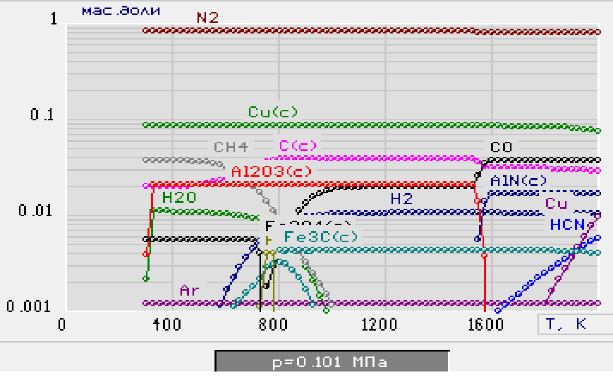


Fig. 7. Composition (in weight fractions) of equilibrium C–H–O–N–Ar–Cu–Al–Fe-system, based on the air + LPG mixture for the conditions of plasma-fuel spraying of bronze coating at the value of ER = 0.10 (partial oxidation + pyrolysis of LPG-gas medium) for T = 300–2000 K, p = 0.1 MPa

Experimental results

Taking into account the data on the preferred regimes of the plasma-fuel process, a series of experiments has been carried out with our upgraded plasma spraying system at power of up to 40 kW, operating on the base of the UPU-3D unit using the combination of three gases – technical quality nitrogen, propane-butane (i.e. liquefied petroleum gas, LPG) and low-pressure air from compressor. The experiments are required to determine the parameters of the system for spraying of metal materials onto samples corresponding to metal parts of machinery industry and medical sectors. For this purpose, the use of modern design methods for fabrication of the fuel intensifier with flexible variable geometry (including laser LOM technologies), joined with DC arc plasma torch of PP-25 type, has been carried out. Figure 8 shows photos of the plasma-fuel system, based on the DC torch, for chosen powder spraying method at different operating regimes. The additional equipment for the spray system has been also applied in the form of tubular metal shroud, contributing to increase in energy efficiency of the test unit, as well as protection of metal powders against thermal oxidation during spray. For the obtained coatings with a thickness of 100 to 450 μm (on plate samples from Steel 30) from powder material (commercial aluminum bronze of PG-19M-01 grade, particle fraction from 40 to 100 μm), some structural and functional parameters have been tested using X-ray diffraction (XRD) method for phase analysis, which has shown the opportunity for their use on metal parts for various applications.

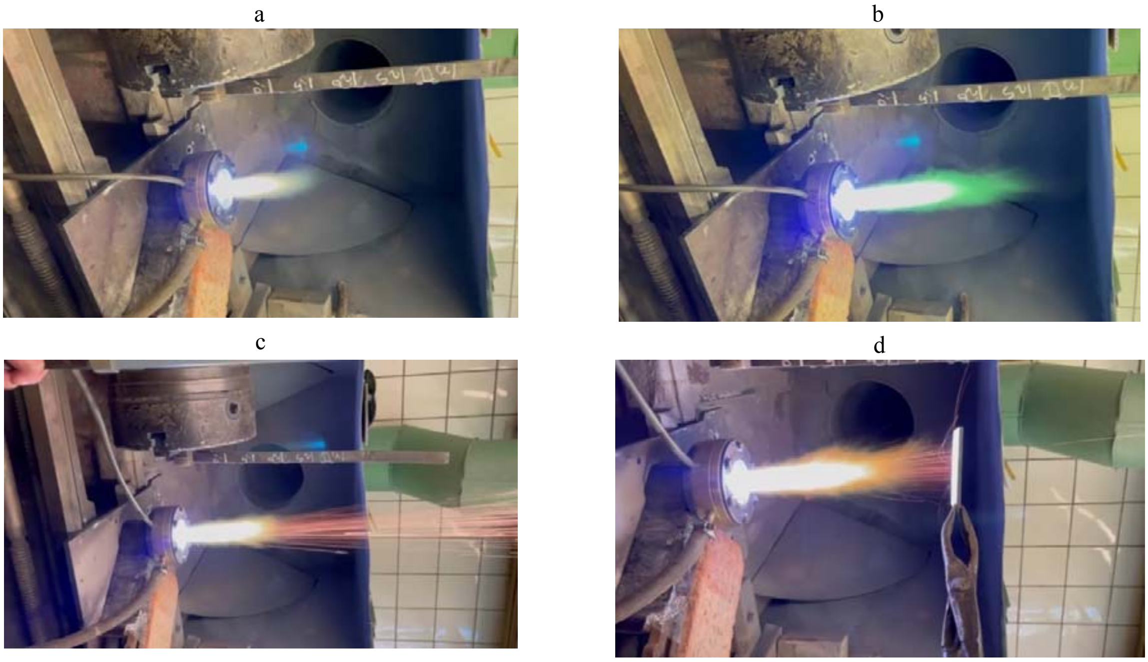


Fig. 8. Views of plasma-fuel system for bronze powder spraying based on PP-25 plasma torch with the fuel intensifier, which is operating during varied experimental conditions: a – regime without feeding of LPG-fuel and the powder and without connection of protective shroud to the intensifier; b – the same regime as for (a), but with LPG-fuel injection; c – the same regime as for (a), but with LPG-fuel injection and powder feeding; d – the same regime as for (c) at the powder spraying on fixed metal substrate of Steel 30 plate

As it has been found, operating capacity of the process reaches 15.0 kg/h for the bronze powder when using a moderate power of the plasma torch – up to 35–40 kW and quite limited flow rate of hydrocarbon gas (LPG of SPBT grade) – 0.25–0.35 kg/h. Special assessment of energy efficiency parameters of this technology, in comparison with plasma and combined equipment of similar purpose, shows that it has an advantage in terms of target indicators (energy consumptions, overall energy efficiency [4, 26] of the device) by at least 20–30 %.

On the composition and parameters of obtaining coatings

The samples of coatings obtained by spraying in the described modes of the plasma-fuel process have undergone visual control of their quality (roughness, presence of visible defects, quality of adhesion to the surface of steel substrate/piece) and measuring of their thickness with micrometer. In addition, we have carried out optical-microscopic evaluation of porosity and structure of coatings using microscope MICRO 200-01 (Russia) with a magnification of up to 1000 times. This evaluation confirmed the micrometrically found value of typical coating thickness (near 200 μm) for the case of sprayed coatings from bronze powder of PG-19M-01 grade, obtained in optimized technological regime (with flow rate of nitrogen through the plasma torch G_{N_2} = 1.2 g/s and flow rate of LPG + air mixture $G_{f\text{-}a}$ = 1.65 g/s, with an equivalence ratio of the mixture ER ≈ 0.5, i. e. in the regime of not fuel combustion process, but partial oxidation of LPG). It also showed slight porosity of the coating in all areas and the absence of its undesirable flaking [2] from the substrate.

Micrograph images from different zones of this sample are shown in Fig. 9, and before making a thin section of this sample, part of its frontal surface was treated with mechanical polishing (Fig. 9d). It is important, that detected moderate porosity in the coatings produced from this material does not prevent their functional application. This includes both coatings for machinery plants sector (e. g. those involving work with lubrication of the surface of parts), and coatings for use in metal parts/pieces and indoor equipment (including metal fittings, etc.) for medical institutions [17, 27], where not so much mechanical strength of metal coatings or corrosion protection effect but their efficient antimicrobial action is typically required.

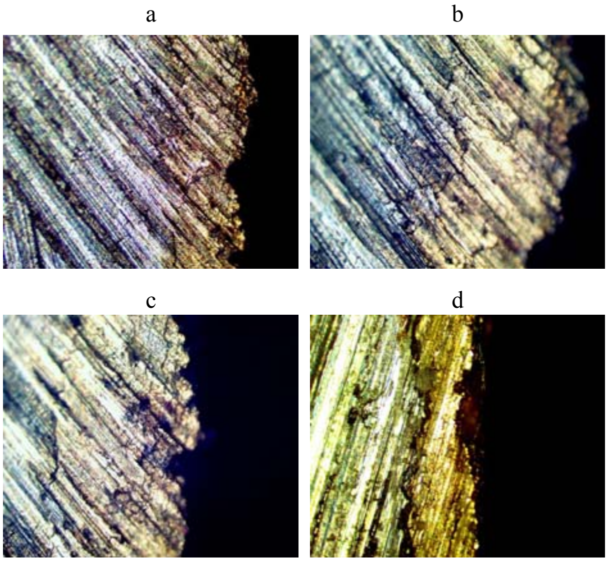


Fig. 9. Micrographs of cross section of cut samples with sprayed bronze coatings (gold-like color in the images) on the Steel 30 substrate at the scale: a – ×100; b – ×200; c – ×200; d – ×100 at mechanical polishing of the prepared cross section with the coating

X-ray diffraction analysis to study the composition of the coated samples was performed by us with using the diffractometer from Bruker D8 ADVANCE (USA) with CuKα-radiation (the wavelength λ = 0.15418 nm) in automatic registration mode, using a nickel filter (performed at the JIME of NASB). The phase composition of the samples was determined from obtained diffraction patterns using the EVA software, with using the PDF-2 (powder diffraction file) database of the International Center for Diffraction Data. The XRD-plot is shown in Fig. 10 as one of the examples of the resulting diffraction patterns. This analyzed sample shows the following four main phases in the coating:

a) intermetallic Cu_3Al (ICDD card (in the XRD database) #28-0005, space group for the phase – P(0)) – 23.1 wt. %;

b) metal Cu (ICDD card #04-0836, space group Fm-3m (#225) – 68.9 %);

c) intermetallic CuAl (ICDD card #65-1228, space group C2/m (12), monoclinic crystal system) – 6.6 %;

d) oxide $Fe_{0.95}O$ wüstite (ICDD card #79-1967, space group Fm-3m (#225) – 1.4 %.

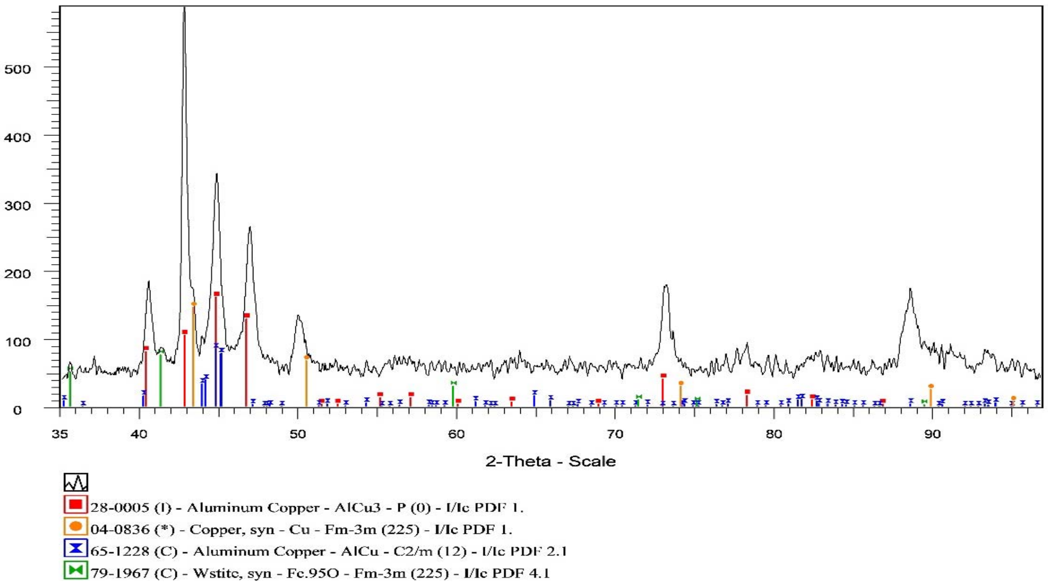


Fig. 10. X-ray diffraction pattern for the plasma sprayed (with FA-APS technology) copper alloy coating (bronze)

Other theoretically possible impurities (copper and aluminum oxides, Fe_3C) are negligible in the sprayed coating.

This coating composition (likely due to the increased residence time of the sprayed powder in plasma jet used in our combined fuel-plasma system) is somewhat different from the results obtained from the literature data for plasma sprayed coatings of similar alloys, in particular, in [28]. In this the analysis of bronze coatings obtained by the standard APS method (from bronze of PG-19M-01 grade) showed that the main phase in the coating is solid solution of aluminum in copper with a crystal lattice parameter (unit cell) a = 0.36479 nm (cubic lattice), which is higher than the lattice parameter of pure copper phase a = 0.361479 nm.

In addition, taking into account potential medical application of copper-alloy based coatings, one should pay attention to such coating parameter as their chemical composition. Overview of numerous (especially in the last 2–3 years) publications has shown that it is recognized fact that copper and coatings with it are quite economical and safe means for disinfection and have antimicrobial properties, and copper acts even more efficient than materials with silver ion concentration [29]. The US Environmental Protection Agency (EPA) has verified antimicrobial efficiency of more than 500 different copper-based alloys with an average biocide activity of approximately 99 % for alloys with ≥60 % of copper content. Thanks to similar results obtained in USA and other countries, Cu and its alloys are certified as effective anti-pathogenic agent for surface applications [30].

Used bronze powder of PG-19-M-01 grade for our spraying experiments corresponds to Russian technical standard “TU 48-4206-156-82” (manufactured by Torez plant of surfacing hard alloys, Donetsk). Its chemical composition according to the manufacturer’ data is 9–11 wt. % Al, and ≤ 4 % Fe, and the rest is Cu. With this composition, the sprayed coatings of this type, which have been obtained with our investigated technology and other related ones will have, as expected, antimicrobial effect with quite high probability [31].

We have carried out special chemical test using the release of copper ions on the surface of the coatings upon contact with dilute solution containing $NH4^+$ compounds, which results in formation of blue colored copper-ammonia fragmented precipitate, indicating the presence of trace concentrations of Cu^{+2} ions in humid media. This, according to the literature data, makes it possible to classify such coatings as having increased antimicrobial activity, if their material/alloy contains above mentioned fraction of copper (>60 %). Figure 11 shows photos of one of the samples with the coating sprayed in our experiment, and part of its surface (which had a roughness class of no higher than the sixth after the spraying deposition) was mechanically polished before the chemical test. This test for the presence of copper ions on the sample surface confirmed presence of Cu^{+2}, which, within a few seconds after contact with dilute ammonia solution in water, has given microcrystalline blue precipitate, both on initial relatively rough surface after deposition and on the polished part of this coating.

It is also possible to note that in addition to the type of bronze powder, which has been used in our spraying experiments in investigated method for upgraded spraying, some other bronzes (which, unlike L63-grade brass or similar alloys, do not contain elevated concentrations of easily vaporizing zinc in alloy composition) are applicable. For example, commercial grade (PR-BrAZhNMts 8.5-4-5-1.5) can be used, which is produced at plant of Polema Co (Russia). In accordance with the manufacturer's classification, this is bronze powder (sprayed with gas) for coatings producing with such elemental composition of the powder as: Al – 8.5 wt. %, Fe – 4 %, Ni – 5 %, Mn – 1.5 %.

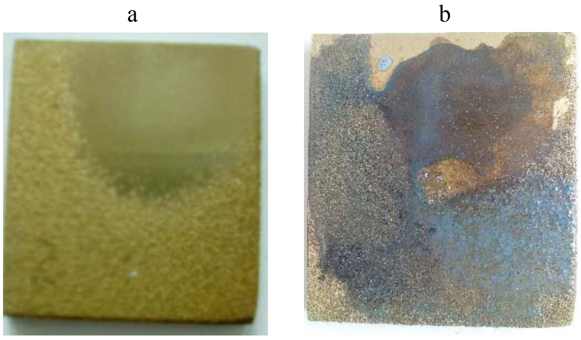


Fig. 11. Photos of steel plates (as the simulator of parts of medical equipment) with plasma sprayed bronze coating: a – before the chemical test with release of copper ions on the coating surface (part of the pure coating' area is mechanically polished); b – after the chemical test, in which the formation of blue-colored copper-ammonia precipitate (fragmented hydrated crystals) was formed

The set of found results allows us to offer technical recommendations for next industrial applications, taking into account the following average engineering and economic indicators of the new FA-APS spraying technology (using Cu-based (>80 % content) bronze coating for carbon steel pieces as an example), which have been established: sprayed powder material consumption – 1–2 kg per 1 m^2 of treated steel surface (with an average coating thickness of 100 μm); electrical consumption ≤2–3 kWh per kg of sprayed coating; the estimated processing cost of the coating is $30–50 per 1 m^2 of the surface; at the consumption of ≤40 kW power and at the powder utilization factor of 55–60 wt. % [2, 18]. The obtained data can be considered as the basis for new spraying method based on the plasma-fuel equipment of our design, which is patentable, in particular, in a relation to metal coatings from powder materials based on alloys of copper and other nonferrous metals.

CONCLUSION

Analysis of the obtained results on the spraying process regimes and produced bronze coating parameters (including the XRD-data for one of the samples), in a combination with some energy efficiency parameters of the developed technology, as well as its calculated technical characteristics, in a comparison with plasma and combined equipment of a similar purpose, has shown that it has an advantage in terms of target indicators, in particular, in terms of energy consumptions and total energy efficiency of the spraying unit, not less than 20–30 %. Operating capacity of our upgraded process is established to reach the level of 7–15 kg/h for aluminum bronze powder spraying when using power of plasma torch ≤ 35–40 kW and a limited flow rate of fuel gas (such as LPG) 0.1–0.35 kg/h. These results give the opportunity for the next stage of the subsequent application of this technology into production based on a new combined process for the bronze coating spraying, in particular with antimicrobial properties, with improved energy efficiency of the process.

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