UDC 621.793.7

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PERSPECTIVES OF IMPROVING PHYSICAL AND MECHANICAL PROPERTIES OF THERMAL COATINGS BY ELECTROPULSE EXPOSURE

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ПЕРСПЕКТИВИ ПІДВИЩЕННЯ ФІЗИКО-МЕХАНІЧНИХ ВЛАСТИВОСТЕЙ ГАЗОТЕРМІЧНИХ ПОКРИТТІВ ЕЛЕКТРОІМПУЛЬСНОЮ ДІЄЮ

Purpose. To explore the possibility of raising the physical and mechanical properties of electric-arc and plasma sprayed coatings by electric pulse exposure (EPE) on high temperature heterophasic stream during deposition and subsequent pre-recrystallization heat treatment (PHT).

Methodology. Study of porous electric arc and plasma sprayed coating was carried out using a computer metallography. Vickers hardness was determined. The study of thermal properties of coatings was carried out by using a dynamic calorimeter. The bond strength of the coating was determined by “pulling the pin” on the witness samples. Determination of wear resistance of the resulting coatings was performed on the SMC-2 machine friction on a “roller-shoe” in the boundary lubrication conditions. The definition of regions of coherent x-ray scattering to estimate the size of the substructure of the coating material was carried out by X-ray analysis on a DRON-3.

Findings. The optimum amplitude and frequency parameters of EPE at electric arc spraying of Sv-08G2S wire (pulse frequency – 6.5 kHz, the amplitude – 5 kV) and PG-19M-01 powder plasma spraying (frequency – 5 kHz, the amplitude – 5 kV) were determined, which provide increased hardness (up to 35 %), density, bond strength (to 30 %) and the wear resistance of the coatings (1.5...1.7) by grinding and accelerating sprayed particles. The optimum temperature-time parameters of PHT that provide a further increase in the hardness of the coatings by grinding sub grain size to nanoscale inclusive were defined. The possibility of thermal stabilization poligonization substructure of coatings by plastic deformation was investigated.

Originality. The laws of EPE influence on the microstructure and mechanical properties (hardness, bond strength, thermal conductivity, wear resistance) of electric arc and plasma coatings were determined. The technology PHT sprayed coatings in the direction of increasing the exposure time due to subsequent plastic deformation was further developed.

Practical value. The application of research results obtained in the work, namely the definition of the scheme of the connection of high-voltage pulse, the optimal parameters of EPE during electric arc and plasma spraying and subsequent heat treatment provide the opportunity to expand the range of cheaper sprayed materials for the coatings of heavily loaded parts of mechanical engineering, electrical products and parts of the military-industrial complex.

Keywords: *thermal coatings, heat treatment, electric pulse exposure*

Introduction. The issue of improving the reliability of equipment, ensuring its competitiveness, as well as extending the service life and renovation is an actual problem of modern production. One of the most fundamental and priority ways of solving these problems is to apply coatings on the surface of parts and structures. Among the various methods of developing them, one of the most useful is the group of thermal spraying methods, including electric arc and plasma, which have proliferated in recent years.

Electric arc spraying is characterized by its simplicity and adaptability, high material utilization, low cost and high performance. Plasma method allows coverage of a wide range of materials without their melting temperature limit, characterized by an effective control of coating formation process. But along with that, there are inherent disadvantages of both methods, the main ones include a high level of porosity, low bond strength, which is an important characteristic of the coating.

Unsolved aspects of the problem. Analysis of the effectiveness of modern ways of improving physical and mechanical properties of thermal coatings shows that the main result of their use is mainly to provide high-energy parameters of the spray particles and reducing their size. Methods that use pulsed effect on the deposition process, in particular mechanical, acoustic, electric, laser, etc. have been considered promising recently [1, 2]. Among them is the use of electro effects, which is characterized by low power consumption and low cost of additional equipment [3].

Furthermore, one of the ways to increase the properties of the deposited coatings is the use of pre-recrystallization heat treatment, the essence of which is to fix poligonization substructure cooling the coating material at the stage of subgrains to nanoscale size [4]. However, the low velocity of the particles while using the conventional deposition method does not always provide a sufficient degree of deformation to exhibit "size effect".

The objective of the article is to explore the possibility of enhancing the physical and mechanical properties of the electric pulse exposure of electric and plasma coatings on high temperature heterophasic jet during spraying and subsequent predrecrystallization heat treatment.

Presentation of the main research. The object of the study involved electric arc coatings made of Sv-08G2S wire and PG-19M-01plasma coating powder. The electric arc coatings were applied to KDM-2 installation using EM-14M spray in the following mode: the arc voltage – 25 V, the power of the arc current – 110 A, air pressure – 0.6 MPa. The plasma coating was applied on the "Kyiv-7" installation, which is equipped with a PUN-1 plasma torch in the following mode: the arc voltage – 180 V, the power of the arc current – 150 A, spraying distance – 180 mm. Air was used as the plasma and the transport gases. The hardness of the coatings was measured on the Vickers machine with a load of 5 kg. Metallographic studies were performed with an MMU-3optical microscope. The wear resistance of the coatings was determined using the friction machine SMC-2, bond strength of the coatings to the substrate was defined using tensile machine UMM-5. The heat treatment of the resulting coatings was carried out in a laboratory electric furnace SNOL-1.6.2.0.08/9-M1.

A high-power high-frequency electrical saw tooth pulse source, which is connected to the dispensers in a straight line pattern, was used for electric pulse exposure to high temperature heterophasic jet.

Preliminary experiments showed that the use of frequencies up to 4 kHz and voltages up to 5 kV does not significantly affect mechanical properties of coatings and porosity, so respective ranges of frequency (from 4 to 8 kHz) and voltage (5 to 10 kV) of electrical pulses were selected while planning the experiment. To determine the EPE optimal parameters the method of full 2k factorial type experiment was used. The hardness of the coating was used as an optimization parameter. The frequency and voltage were chosen as variable factors. Factors such as current, voltage, spraying distance etc. were recorded on the above conditions. In each mode 5 samples were sprayed, whereupon they were ground to a coating thickness of 0.6 mm and the hardness was measured. Based on the statistically processed experimental data, regression coefficients were calculated, their relevance and the adequacy of the obtained models were verified regarding the actual process of spraying electric arc and plasma coatings by known methods [5]; as a result, the following regression equations were obtained:

- for electric arc spraying

$$Y = 2352 + 171X_1 + 45X_2 - 65X_1X_2;$$

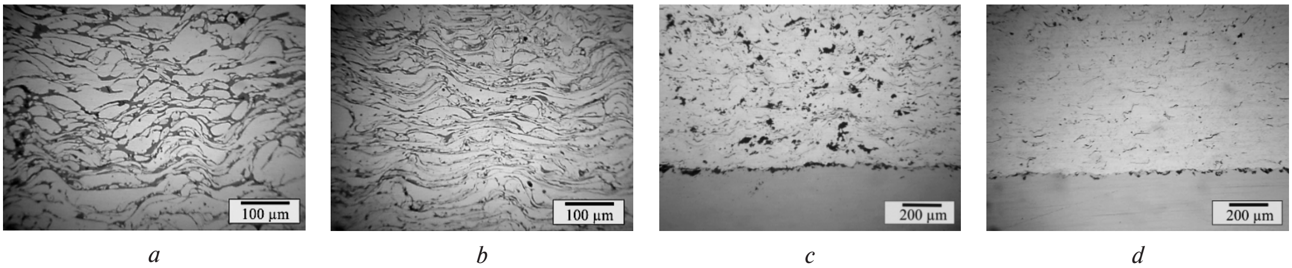
- for plasma spraying

$$Y = 1342 - 62X_1 + 24X_2 - 16X_1X_2.$$

According to constructed models, the EPE parameters were optimized by the method of steep ascent. For electric arc spraying a maximum hardness value was obtained at a frequency of 6.5 kHz, as for a plasma, the frequency was 5 kHz. The value of the voltage was 5 kV.

Microstructure analysis (Fig. 1) indicates that the use of EPE leads to breakage of structural elements of the coating, as well as reduced porosity of 3 to 6 % for electric arc coating and from 8 to 5 % for plasma coating with improved hardness coatings by 35 and 24 %, respectively.

To explain grinding of the resulting coating microstructure, we conducted studies of fractional composition of the spray particles, which is determined by the metallographic method with samples collected during spraying in water. The results showed that when using EPE in the optimal mode, there occurred narrowing of the fractional composition of the particles and a decrease in average size from 84 to 54 microns for electric arc spraying, and from 50 to 42 microns for plasma, indicating to their further crushing in a high temperature jet. It is known [6] that the decrease in inertia of particles, which is associated with crushing, causes an increase in their average speed and reduction of the standard deviation from the mean diameter leads to a reduc-



a *b* *c* *d*

Fig. 1. The microstructure of the sprayed coatings by the conventional method (a – electric arc, c – plasma) and using the EPE (b – electric arc, d – plasma)

tion of the velocity dispersion. This provides a more uniform and dense packing of particles in the coating, with its strength increasing and the porosity decreasing.

In most cases the bond strength is the main characteristic of the coating. In order to determine it, a pin method was used. Samples for adhesion were made of carbon structural steel 45. The surface was degreased and subjected to technical ethanol-blasting treatment. The thickness of the deposited coatings was 0.6 mm. Spraying was conducted on the above conditions. In the course of experimental studies it was found that the bond strength for the electric arc coatings of Sv-08G2S wire deposited using electric pulse exposure increased from 26 to 34 MPa; for those of plasma of PG-19M-01 – from 17 to 22 MPa. The analysis of the samples showed an increase in the number of regions of binding of sprayed coating with the base that provides a reduction of the resulting load per unit area of the sample. This is explained by the effect of increasing speed of the spray particles.

Coating wear was determined by the loss of mass of the sample every 10 km of traveled distance. Analysis of the results of the determination of wear resistance (Fig. 2) showed that the electric arc coating, applied using EPE, has the wear 1.7 times as little as that of the coating, deposited in a traditional way.

Plasma coating sprayed with EPE with the optimal amplitude and frequency parameters, has the wear 1.5 times as little as that of the cover, deposited in a traditional way. Increased wear resistance occurs due to the increase in the hardness of the coatings: arc at 35, 24 % plasma.

The ratio of the thermal conductivity of coatings was determined by measuring the thermal conductivity of the IT-λ-400. The measurement results showed that by using EPE a decrease in thermal conductivity of both electric and plasma coatings on average by 10 % is observed; it occurs due to increase in the number of boundaries between particles.

To further improve the hardness of coatings deposited using EPE, the optimal mode is determined for their pre-recrystallization heat treatment (Fig. 3).

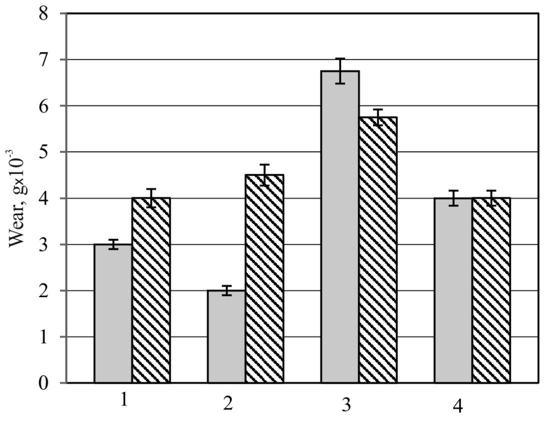
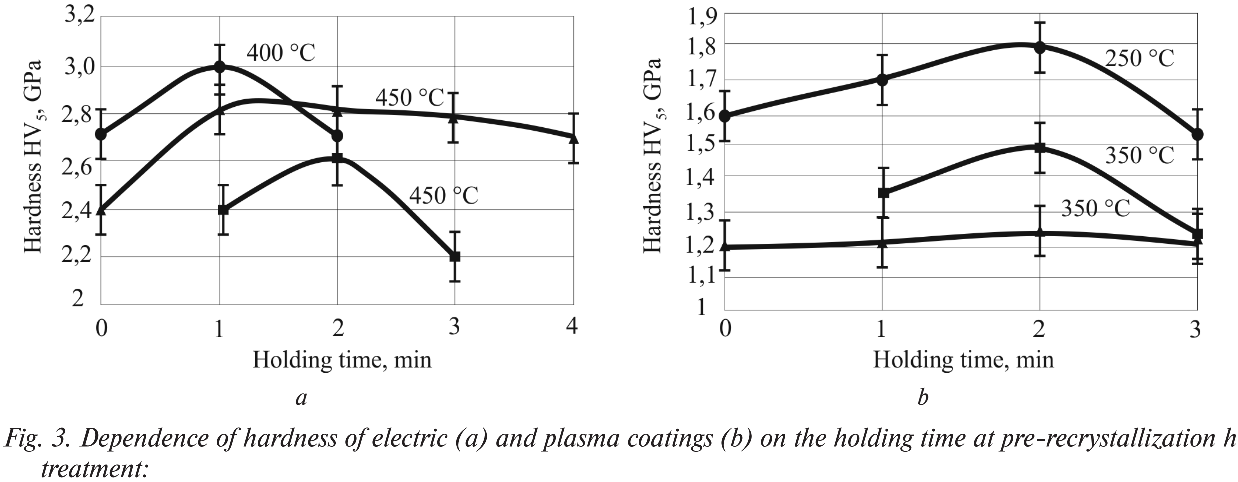


Fig. 2. The results of the wear resistance of plasma (1.2) and electric arc (3.4) coatings:

1, 3 – the traditional way; 2, 4 – using EPE; ▪ *– coating;* ▨ *– counterface*

According to the data it was found that the dependence is of extreme nature with expressive peak, temperature and holding time; thus, it can be considered optimal. Reduction of hardness with increasing duration of exposure occurs due to the increasing sub-grains size caused by increased mobility of sub-boundaries. The hardness value of electric arc coating maximizes after PHT at 450 °C and 2 minutes' holding time to a coating applied by the conventional method from 2 to 2.6 GPa. For the coating deposited using EPE, the optimum holding time is 1 min at 400°C with hardness values increasing from 2.7 to 3 GPa (+12 %).

A similar relationship is observed with the hardness of plasma coatings (Fig. 3, *b*). The optimum heat treatment conditions for the plasma coating of PG-19M-01 powder applied by the conventional method, include heating to a temperature of 350 °C and holding for 2 min, and enhance the hardness by 15 %. As for the coating sprayed using EPE, the optimum heat treatment mode also shifts to lower temperatures and is heated to 250 °C with holding for 2 min. At the same time plasma coating hardness increases from 1.6 to 1.8 GPa (+13 %).



a *b*

Fig. 3. Dependence of hardness of electric (a) and plasma coatings (b) on the holding time at pre-recrystallization heat treatment:

▪ *– the traditional way;* ▲, • *– EPE*

Thus, it can be concluded that, the optimum mode of thermal processing shifts to lower temperatures and lower exposures for the coatings deposited using EPE. This is due to higher degree of deformation of the particles during the formation of coatings because of their high speed.

To quantify the influence of PHT on the substructure of resulting coatings, regions of coherent scattering (RCS) of X-rays were defined (Table).

According to the data presented in Table, while using EPE on high temperature heterophasic jet, a decrease of coherent X-ray scattering occurs in the process of spraying, it is due to refinement of the coating substructure as RCS size is identified with an average crystallite size [7].

After further heat treatment above mentioned coatings, the RCSs have significantly lower values compared to the heat treated coatings obtained by the conventional method. Thus, the RCS of electric arc coating decreases from 106 to 87 nm, and it decreases from 345 to 218 nm for the plasma. Thus, the analysis of the data suggests that conducting PHT produces a crushed subgrain structure of a nanoscale size, inclusive. The cause is that after the heat treatment of coatings deposited with EPE, smaller sub-grains are formed due to the greater degree of deformation of the particles.

The main disadvantage of the PHT is a small duration of exposure of a few minutes, so it is topical to study the possibility of stabilizing shredded poligonization substructure sprayed coating at a slow shutter speed in the process of heat treatment by subsequent deformation, because it will create dislocation barriers and plexus that inhibit the movement of sub-boundaries. To investigate the matter, electric arc coating of 12Cr18N10T was chosen wire since the preliminary experimental studies showed that the thermal treatment provides a greater increase in hardness. The amount of pre-strain was 15 %. The resulting sprayed samples were heated in a furnace to a primary recrystallization onset temperature of the material of the arc coating of 12Cr18N10T wire which is 600 °C.

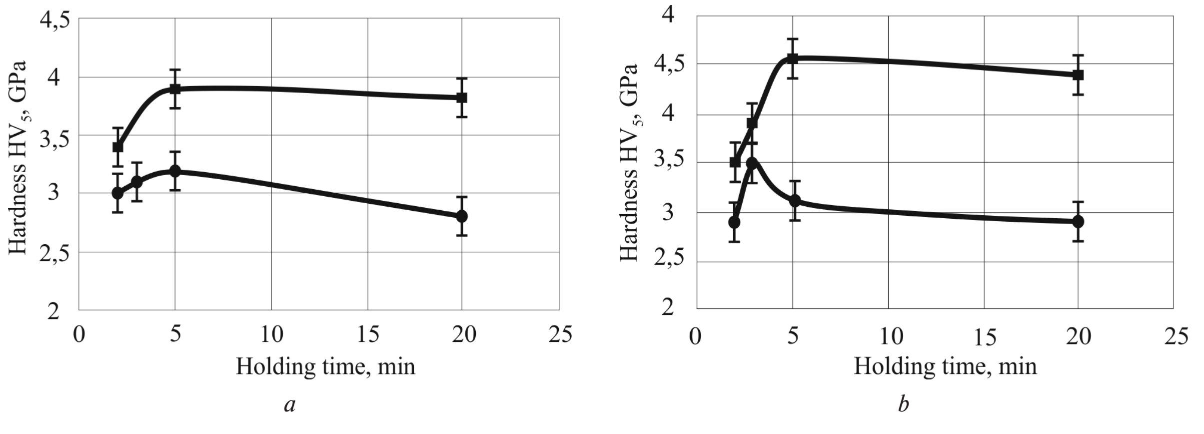
Table

The size of regions of coherent scattering of electric and plasma coatings

Coating	A method of spraying and the amount of deformation of the particles, %	Heat treatment	RCS size, nm
Sv-08G2S	Conventional method. Deformation 83	Without PHT	225
		PHT: 450 °C, 2 min	106
	Using EPE. Deformation 87	Without PHT	205
		PHT: 400 °C, 1 min	87
PG-19M-01	Conventional method. Deformation 80	Without PHT	599
		PHT: 350 °C, 2 min	345
	Using EPE. Deformation 83	Without PHT	534
		PHT: 250 °C, 2 min	218

Optimum PHT parameters are determined according to Vickers hardness (Fig. 4). The results of hardness measurement are shown in Fig. 4. The hardness of the coating after spraying, according to the traditional method was 2.4 GPa. When using EPE it is 2.8 GPa.

Analysis of the graphs shows that the use of subsequent deformation provides a less intensive decrease in hardness with increasing duration of exposure to the PHT coatings up to 20 minutes. This trend is observed for both methods of applying arc coatings. For example, the hardness of the coating, deposited by the conventional method, by increasing the duration of exposure of 5 to 20 minutes without pre-deformation decreases from 3.2 to 2.8 GPa (-13 %), and during the subsequent deformation – from 3.9 to 3.8 GPa (-3 %). However, using EPE during deposition results in increase in hardness after deformation and subsequent thermal treatment (20 min exposure) by 83 %, and using the traditional method – by 58 %. This effect is explained by an increase in the magnitude of deformation of the particles by increasing their speed.



a *b*

Fig. 4. Dependence of hardness of the electric arc coating of 12Cr18N10T wire sprayed by the conventional method (a) and using EPE (b) on the holding time at PHT:

• – after spraying; ■ – after spraying and strain (15 %)

Conclusions. The optimum amplitude and frequency parameters of the EPE of the electric arc spraying of Sv-08G2S wire (pulse frequency – 6.5 kHz, amplitude – 5 kV) and a plasma PG-19M PG-01 powder (frequency – 5 kHz, the amplitude – 5 kV) were determined, which provide increase in hardness by 35 and 24 %, the bond strength by 30 and 18 %, the wear resistance 1.7 and 1.5 fold as well as decrease in porosity from 6 to 3 % and from 8 to 5 %, respectively. The optimum temperature-time parameters of subsequent pre-recrystallization heat treatment, which provides a further increase in hardness by grinding poligonization substructure to nanoscale size, inclusive were obtained. The possibility of increasing the holding time due to subsequent deformation of the coating with the PHT (15 %) was defined. Prospects for further research are to conduct similar experiments with flame and detonation coatings and to optimize deformation and heat treatment for thermal stabilization of poligonization substructure.

References / Список літератури

1. Roianov, V.A. and Bobikov, V.I., 2010. Influence of pulsating spray jets on the structure and microhardness of the coating particles in the arc spraying. *Visnyk Pryazovskoho derzhavnoho tekhnichnoho universytetu*, No. 20, pp. 172–175.

Роянов В.А. Влияние пульсирующей распыляющей струи на структуру и микротвердость частиц покрытий при электродуговой металлизации / В.А. Роянов, В.И. Бобиков; Вісник Приазовського державного технічного університету. – 2010. – № 20. – С. 172–175.

2. Iliuschenko, A.F., Shevtsov, A.I., Okovityiy, V.A. and Gromyko, G.F., 2011. *Protsessy formirovaniia gazotermicheskikh pokrytii i ikh modelirovaniie* [The formation of thermal coatings and their modeling]. Minsk: Navuka.

Процессы формирования газотермических покрытий и их моделирование / Илющенко А.Ф., Шевцов А.И., Оковитый В.А., Громыко Г.Ф. – Минск: Беларус. Навука, 2011. – 357 с.

3. Kadyrmetov, A.M., 2012. Investigation of plasma deposition and hardening of coatings and their quality control path. *Nauchnyiy zhurnal KubGAU*, No. 8, pp. 1–18.

Кадырметов А.М. Исследование процессов плазменного нанесения и упрочнения покрытий и пути управления их качеством / А.М. Кадырметов; Научный журнал КубГАУ. – 2012. – № 8. – С. 1–18.

4. Dubovyi, O.M., Lebedieva, N.Yu. and Yankovets, T.A., 2010. Effect of pre-recrystallization heat treatment on physical and mechanical properties of sprayed coatings and deformed metals and alloys. *Metaloznavstvo ta obrobka metaliv*, No. 3, pp. 7–10.

Дубовий О.М. Вплив передрекристалізаційної термічної обробки на фізико-механічні властивості напилених покриттів та деформованих металів та сплавів / О.М. Дубовий, Н.Ю. Лебедєва, Т.А. Янковець; Металознавство та обробка металів. – 2010. – № 3. – С. 7–10.

5. Pinchuk, S.Y., 2009. *Orhanizatsiia eksperymentu pry modeliuvanni ta optymizatsii tekhnichnykh system* [An experiment in modeling and optimization of technical systems]. Dnipropetrovsk: Dnipro-VAL.

Пінчук С.Й. Організація експерименту при моделюванні та оптимізації технічних систем / Пінчук С.Й. – Дніпропетровськ: „Дніпро-VAL“, 2009. – 289 с.

6. Petrov, S.V., 2004. Methods of radical increasing quality of thermal sprayed coatings. *Oborudovanie i instrument dlya professionalov*, No. 10, pp. 2–5.

Петров С.В. Методы радикального повышения качества газотермических покрытий / С.В. Петров; Оборудование и инструмент для профессионалов. – 2004. – № 10. – С. 2–5.

7. Gusev, A.I. and Kurlov, A.S., 2008. Certification of nanocrystalline materials in particle size (grains). *Metallofizika i noveyshie tehnologii*, No. 5, pp. 679–694.

Гусев А.И. Аттестация нанокристаллических материалов по размеру частиц (зерен) / А.И. Гусев, А.С. Курлов; Металлофизика и новейшие технологии. – 2008. – Т. 30. – № 5. – С. 679–694.

Мета. Підвищення фізико-механічних властивостей електродугових і плазмових покриттів електроімпульсною дією (ЕІД) на високотемпературний гетерофазний струмінь при напиленні та подальшою їх передрекристалізаційною термічною обробкою (ПТО).

Методика. Дослідження пористості отриманих електродугових і плазмових покриттів здійснювали за допомогою комп'ютерної металографії. Твердість визначали на приладі типу Віккерс. Вивчення теплофізичних властивостей покриттів проводили за методом динамічного калориметра. Міцність зчеплення покриттів з основою визначали методом „витягування штифта“. Визначення зносостійкості отриманих покриттів проводили на машині тертя СМЦ-2 за схемою „ролик-колодка“ в умовах обмеженого змащування. Визначення областей когерентного розсіювання рентгенівського випромінювання для оцінки розмірів субструктури матеріалу покриття здійснювали методом рентгеноструктурного аналізу на установці ДРОН-3.

Результати. Визначені оптимальні амплітудно-частотні параметри електроімпульсної дії при електродуговому напиленні дроту з Св-08Г2С (частота імпульсів – 6,5 кГц, амплітуда – 5кВ) і плазмовому напиленні порошку ПГ-19М-01 (частота – 5 кГц, амплітуда – 5 кВ), що забезпечують підвищення твердості (до 35 %), щільності, міцності зчеплення (до 30 %) і зносостійкості покриттів (у 1,5...1,7 рази) за рахунок подрібнення й прискорення напилюваних частинок. Встановлені оптимальні температурно-часові параметри ПТО, що забезпечують подальше підвищення твердості покриттів за рахунок подрібнення субзерен до наномасштабного розміру включно. Встановлена можливість термічної стабілізації полігонізаційної субструктури покриттів шляхом пластичної деформації.

Наукова новизна. Встановлені закономірності впливу ЕІВ на мікроструктуру та фізико-механічні властивості (твердість, щільність, міцність зчеплення, теплопровідність, зносостійкість) електродугових і плазмових покриттів. Отримав подальший розвиток процес ПТО напилених покриттів у напрямі термічної стабілізації полігонізаційної субструктури за рахунок подальшої деформації.

Практична значимість. Застосування результатів досліджень, отриманих у роботі, а саме визначення схеми підключення джерела високовольтних імпульсів, оптимальних параметрів ЕІВ при електродуговому й плазмовому напиленні покриттів та подальшої їх термічної обробки надають можливість розширити номенклатуру дешевших напилюваних матеріалів для нанесення покриттів на важко навантажені деталі машинобудування, електротехнічних виробів і деталей військово-промислового комплексу.

Ключові слова: *газотермічні покриття, термічна обробка, електроімпульсна дія*

Цель. Повышение физико-механических свойств электродуговых и плазменных покрытий электроимпульсным воздействием (ЭИВ) на высокотемпературную гетерофазную струю при напылении и последующей их предрекристаллизационной термической обработкой (ПТО).

Методика. Исследование пористости полученных электродуговых и плазменных покрытий осуществляли с помощью компьютерной металлографии. Твердость определяли на приборе типа Виккерс. Изучение теплофизических свойств покрытий проводили по методу динамического калориметра. Прочность сцепления покрытий с основанием определяли методом „вытягивания штифта“. Определение износостойкости проводили на машине трения СМЦ-2 по схеме „ролик-колодка“ в условиях ограниченной смазки. Определение областей когерентного рассеяния рентгеновского излучения для оценки размеров субструктуры материала покрытия осуществляли методом рентгеноструктурного анализа на установке ДРОН-3.

Результаты. Определены оптимальные амплитудно-частотные параметры ЭИВ при электродуговом напылении проволоки Св-08Г2С (частота импульсов – 6,5 кГц, амплитуда – 5 кВ) и плазменном напылении порошка ПГ-19М-01 (частота – 5кГц, амплитуда – 5 кВ), которые обеспечивают повышение твердости (до 35 %), плотности, прочности сцепления (до 30 %) и износостойкости покрытий (в 1,5...1,7 раза) за счет измельчения и ускорения напыляемых частиц. Установлены оптимальные температурно-временные параметры ПТО, которые обеспечивают дальнейшее повышение твердости покрытий за счет измельчения субзерен до наномасштабного размера включительно. Установлена возможность термической стабилизации полигонизационной субструктуры покрытий путем пластической деформации.

Научная новизна. Установлены закономерности влияния ЭИВ на микроструктуру и физико-механические свойства (твердость, плотность, прочность сцепления, теплопроводность, износостойкость) электродуговых и плазменных покрытий. Получил дальнейшее развитие процесс ПТО напыленных покрытий в направлении термической стабилизации полигонизационной субструктуры за счет последующей деформации.

Практическая значимость. Применение результатов исследований, полученных в работе, а именно определение схемы подключения источника высоковольтных импульсов, оптимальных параметров ЭИВ при электродуговом и плазменном напылении покрытий и последующей их термической обработки предоставляют возможность расширить номенклатуру более дешевых напыляемых материалов для нанесения покрытий на тяжело нагруженные детали машиностроения, электротехнических изделий и деталей военно-промышленного комплекса.

Ключевые слова: *газотермические покрытия, термическая обработка, электроимпульсное воздействие*

Рекомендовано до публікації докт. техн. наук В. Ф. Квасницьким. Дата надходження рукопису 13.04.16.