



Investigation of the properties of coatings obtained by electric arc spraying

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Received: 19 January 2022; Revised: 20 February 2023; Accept: 08 March 2023

Abstract

The paper considers possibilities to increase the wear resistance, corrosion resistance, and service life for parts of machines and mechanisms via their hardening and renovating using electric arc coatings characterized by high density, adhesion strength, and micro hardness. Also, the possibility of controlling the properties of restored surfaces owing to choice of the related equipment with required structure and characteristics in order to prolong the service life of machinery parts is shown. The right choice of equipment for spraying makes it possible to increase the speed and temperature of the spraying gas and particles, reduce the droplet diameter, increase the density and reduce the oxidation of coatings. The influence of spray factors such as the flow rate and pressure of working gases, composition of combustion mixture, spraying distance, dispersion of the spray, properties of wire material, etc. on the properties of the coatings obtained has been investigated.

Key words: coatings, wear resistance, adhesion strength, electric arc spraying

Introduction. The state of the problem and the purpose of the research. In the practice of restoring and hardening parts through the use of hardening protective coatings, extensive experience has been accumulated in the application of coatings by methods of gas-thermal spraying (GTS) [1,2]. The reasonability of using GTS is evidenced by the appearance of a number of special firms for manufacture of equipment and materials for spraying, for example, Metko, Wall Cobmonoy Corp. Linde Div., Union Carbide Corp. *et al.* [3]. The produced domestic and foreign GTS units [1,2], spray materials [3], and published recommendations have made it possible to solve a series of items related to the repair, restoration, and prolongation of the service life of parts [1,2].

In the development of techniques for restoration of parts, it is necessary, of all the possible GTS methods (Table 1) [1,2], to choose such one that provides the longest service life of a part and the lowest cost of its recovery as well as can be fairly versatile, simple, and easy to implement [3]. When choosing a method for GTS, it is necessary to consider the basic conditions for high-quality coating formation [4]:

- 1) thermal effects on the part must prevent the phase or structural transformations in the base metal;
- 2) participation of the base metal in the coating must be negligible;
- 3) in the contact zone, no relaxation process capable to change its phase composition and structure should arise.

Table 1

Characteristics of spraying modes

Parameter	Spraying mode			
	Electric arc	Gas flame	Plasma	Detonation
Efficiency, kg/h	3 - 31	1 -10	0.5 - 8.0	0.1- 6.0
Coefficient of material consumption	0.8 -0.9	0.8 -0.95	0.4 -0.9	0.3 - 0.6
Adhesion strength, MPa	to 40	to 50	to 60	to 200
Temperature of part heating, °C	100-150	100-150	150 -200	100-150



From the standpoint of these conditions, the use of electric arc spraying (EAS) is promising [4,5]. In the world practice of hardening, recovery, and anticorrosion protection, EAS has become widespread as the most technologically advanced and productive method (productivity is 3-4 times that for flame spraying) [4,5]. EAS is widely used in the European countries and displaces the traditional gas-flame method [3]. This is due to the simplicity of the equipment, the availability of energy source for metal melting, higher thermal efficiency, which reaches 57% compared to 13 and 17% for gas and flame spraying [4,5]. The quality of EAS coatings are practically the same as that of coatings produced by plasma and detonation methods, and the coating-to-base adhesion strength is greater than in the case of flame spraying. In [4,5], information is given about the advantages of EAS over surfacing in terms of labor input and consumption of electrode material: duration of surfacing is 1 h 10 min and wire consumption 1.3 kg, while for EAS these parameters are 24 min and 0.95 kg, respectively.

The equipment on which coating is performed is relatively simple and light and can be moved fairly quickly (Fig. 1). The part dimensions do not limit the use of EAS [4,5]. This method is effective and economical in the manufacture and renovation of parts in the conditions of repair enterprises and small workshops with a single production [4,5].

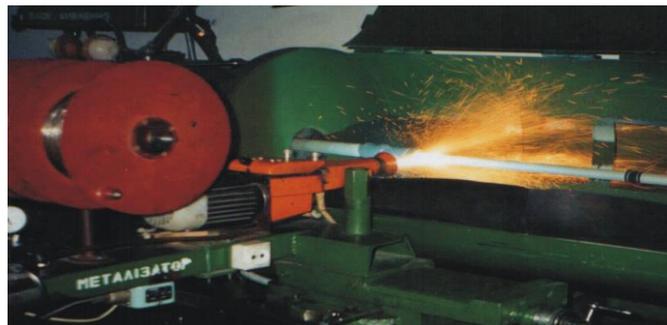


Fig. 1. The electric arc spraying process

Despite the large number of innovations concerning EAS, researches on the improvement of this method and required equipment are actively being carried out and has become aimed at activating the spray process using various techniques, methods, and devices. The spray process activation is the basis for improving the technology and equipment for deposition of high-density wear-resistant layers. In practice, the following procedures for spray process activation have been implemented [1-7]:

- intensification of mixing working gases;
- provision of sprayed particles and the substrate with additional energy via heating them;
- diminution of the sprayed particles size;
- activation of the particle and the substrate surfaces by mechanical methods (increase in roughness) or by reduction of oxides;
- increase in the enthalpy of the spray flux by introducing thermo-reactive components;
- coating with the use of external effects (ultrasonic waves, electromagnetic fields, etc.);
- heat treatment or chemical heat treatment of coatings, etc.

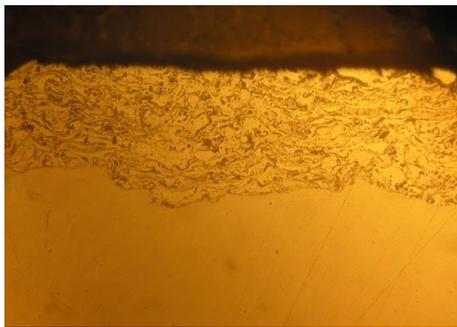
Preheating of the substrate was established to lead to decreasing the rates of crystallization, cooling of falling particles, and developing their chemical interaction with the substrate. As a consequence, adhesion strength increases. However, in the case of heating above 500 K, the rate of oxide formation increases and adhesion strength decreases. Moreover, preheating to 500 K is impossible when thin-walled parts are coated because of unavoidable thermal deformation, and this operation is undesirable in restoring parts that operate under alternating or cyclic loads (as fatigue cracks grow under heating). The use of activation techniques which intensify heat exchange processes in the "jet-particle" system and increase the dynamic parameters of particles, and allows reducing the wire particle size or of those that allow modifying (strengthening) the sprayed layer seems to be most expedient means [8-10].

The aim of the work - was set up to increase the wear resistance and service life of parts *via* combining EAS coatings characterized by high density, adhesion strength, and microhardness due to the activation of the spray process and nitriding of the coatings sprayed.

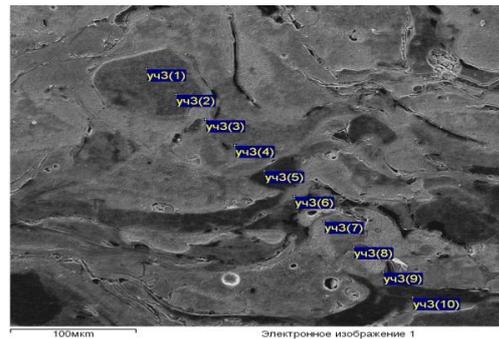
Study of the spraying process and the influence of its factors on the properties of EAS coatings.

The EAS process coating is the result of the following physicochemical interactions: the air flow with the wire melt and the formation of a jet of sprayed particles; transformation of the kinetic energy of the sprayed particles into the work of deformation during their mechanical contact with the part surface, and the transfer of internal (thermal) energy from the particles to the part. On the part surface, a coating layer is formed (Fig. 2), the properties of which depend on the characteristics of physicochemical processes listed above.

The study of the microstructure was carried out on unetched and etched sections using a light microscope "MeF-3" company "Reichert" (Austria) at a magnification of '100, '200, '500. Photos of microstructures are attached (Fig. 2). The study was also carried out on a CamScan scanning electron microscope (Oxford Instruments, England) with an X-ray energy dispersive analyzer (Fig. 2). The morphology (topography) of the coating surface was studied in the mode of reflected electrons at an accelerating voltage of 10–20 kV. The resolution of this SEM is 70 Å. Two types of studies were used: the spectrum from the surface of a thin section and the structure of the surface in combination with Y-modulation, i.e. - slow scanning of the electron beam along the line with the registration of X-ray radiation for each element with and the construction of concentration distribution curves. In addition, spot X-ray microanalysis was carried out according to the program of quantitative analysis. The research results are presented in tables (Fig. 2). The color in the photograph determines the concentration: black - the complete absence of the element, white - 100% presence, transitional colors indicate an intermediate concentration. In the second case, we obtain the distribution of three or more elements at the same time, while each of the elements is assigned a conditional color. All other colors are formed when the three main colors are superimposed and indicate the joint presence of elements in one or another part of the sample, and the concentration in this case is determined by the density of the color. The application of this research program gives very good results for understanding the mechanisms of diffusion processes.

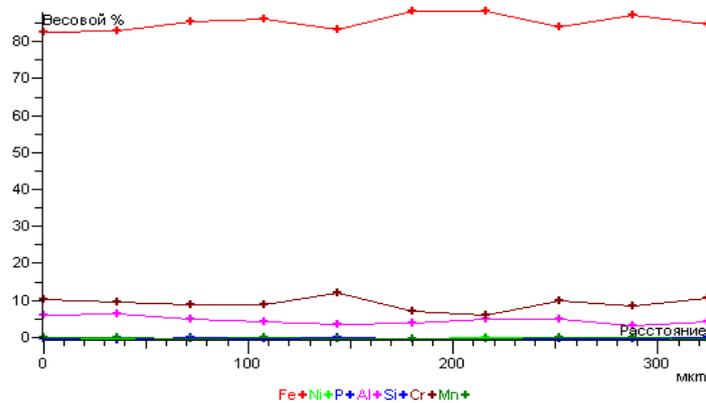


x 200



(b) x250

Спектр	Al	Si	P	Cr	Mn	Fe	Ni
уч3(1)	6.23	0.32	0.10	10.58	0.26	82.56	0.15
уч3(2)	6.69	0.37	0.20	9.97	0.20	82.92	0.05
уч3(3)	5.27	0.12	0.21	9.09	0.06	85.25	0.01
уч3(4)	4.45	0.12	0.04	9.12	0.23	86.12	0.09
уч3(5)	3.98	0.21	0.04	12.47	0.05	83.36	0.04
уч3(6)	4.09	0.15	0.14	7.26	0.10	88.40	0.15
уч3(7)	5.32	0.08	0.10	6.19	0.04	88.20	0.27
уч3(8)	5.26	0.22	0.09	10.21	0.20	83.99	0.02
уч3(9)	3.59	0.20	0.03	8.88	0.16	87.07	0.07
уч3(10)	4.44	0.27	0.21	10.75	-0.14	84.59	0.12



g)

Fig. 2. Microstructure of EAS coatings from wire from powder wire FMI-2 (a, b) and distribution of alloying element (g)

Studies of the effect of the average particle size of spray wires from 40Kh13, 12Kh18N10T, nichrome and powder wire FMI-2 on the physico-mechanical properties of coatings revealed (Fig. 3) that coatings made from steel wires show a decrease in adhesion with increasing porosity, whereas nichrome does not obey this rule. As seen in the figure, the curve of accumulated weight wear of tempered steel has a characteristic stage of running-in and a steady wear stage with almost linear dependence of the weight wear on the friction path. For EAS coatings, the stages of steady wear periodically alternate with the relatively short-term stages of accelerated wear, i.e., wear of EAS coatings is pronouncedly cyclical. The highest averaged weight wear rate was 0.39 mg/m (Table 2).

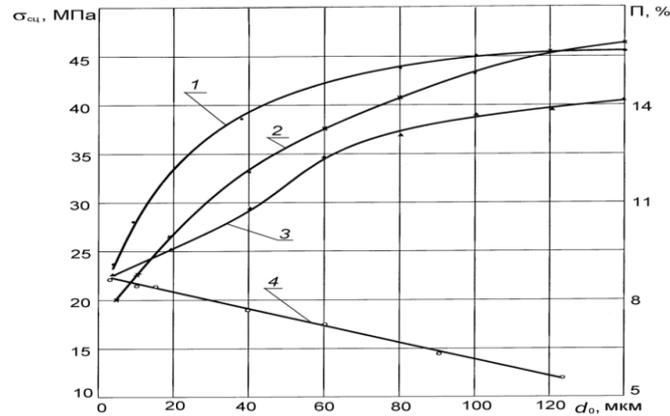


Fig. 3. The effect of the average size of sprayed wire particles of powder wire FMI-2 (1) and of steels 40Kh13, Kh18H10T (2, 3), and nichrome (4) on the adhesion strength (1, 2, 4) and porosity (3) of coatings

Table 2

Wear rate and coefficient of dry friction for EAS coatings and tempered powder wire FMI-2

Material	Wear rate, mg/m	Coefficient of friction
Powder wire FMI-2	0.12	0.82 – 0.93
EAS coating	0.27	0.83 – 0.96
EAS coating	0.39	0.94 – 1.02

Accelerated tribological tests of samples with EAS coatings from powder wire FMI-2 were conducted on an upgraded machine of the 2070 SMT-1 type. Upon spraying, an irregular coating structure was formed *via* layered stacking of molten steel droplets (Fig. 5). Such a structure provides damping of elastic excitations caused by friction. After the tribological tests, no noticeable wear of EAS coatings was detected for 9 h.

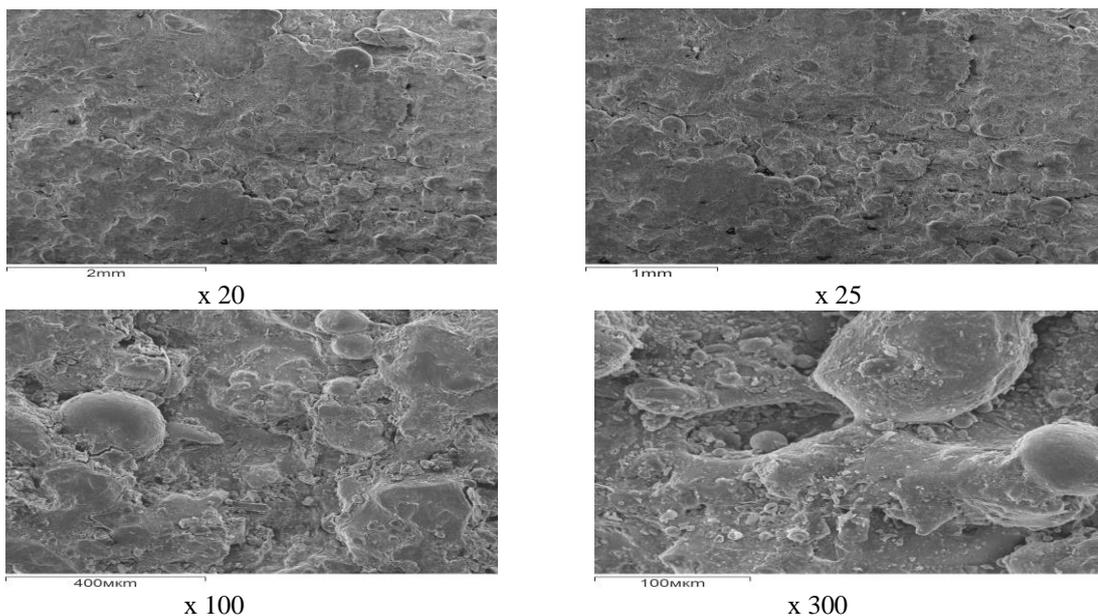


Fig. 5. Surface topography of EAS coating after 9 h testing obtained with a scanning electron microscope
Control of structure formation processes in sprayed coatings

A number of researchers have noted that the structure of coatings obtained by spraying the same wire material by different modes can differ not only in the number of pores, but also in the phase composition [1-7]. This paper presents the results of studies of the structural features of EAS coatings. As spray materials, FMI-2 powder wires with a diameter of 2 mm were used. Spraying was performed using an apparatus for EAS in the following modes:

- mode 1: spraying of metal melted in an electric arc with a reactive jet of combustion products of propane/air mixture with an excess of propane (reducing atmosphere);
- mode 2: spraying of metal melted in an electric arc with a reactive jet of combustion products of the propane/air mixture with an excess of air (oxidizing atmosphere);
- mode 3: spraying of metal melted in an electric arc with a fast air jet.

To improve the adhesion of coatings to a steel 3 substrate, an intermediate layer from powder wire FMI-2 was created. The velocity of molten particles was 120–130 m/s (modes 1 and 3) and 400–500 m/s (modes 1 and 2). The sizes of the particles from which the coatings were formed fell in the range of 5–40 μm . The dominant amount of oxides was formed as a result of the molten particles/air contact. In the work, the effect of the spraying air flow rate on the amount of oxygen in the coatings obtained by EAS (mode 3) was studied (Fig. 6). Here the oxygen content in EAS coatings was 2.5–3 times that in gas-flame ones (Fig. 6), with achieving the maximum concentration 3.8% at flow rates of about 0.5 m^3/min . An XRD analysis (diffractometer DRON-3.0, monochromatic $\text{CoK}\alpha$ radiation, $V = 30 \text{ kV}$, $I = 10 \text{ mA}$) revealed that the phase composition of the coatings includes: α -phase (martensite), γ -phase (austenite), oxides Fe_3O_4 , $\gamma\text{-Fe}_2\text{O}_3$ (traces), and Cr_2O_3 (traces) (Fig. 6).

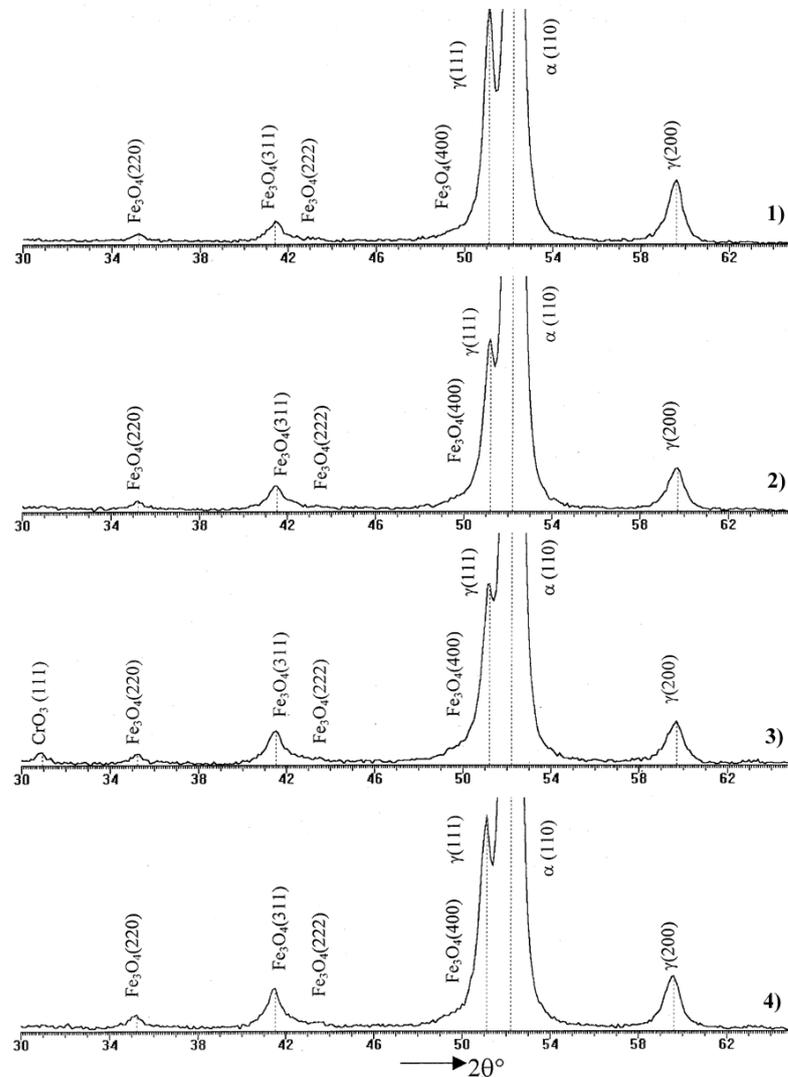


Fig. 6. Fragments of XRD patterns ($\text{CoK}\alpha$) from surface layers of gas-thermal coatings obtained under modes 1-4

The hardness of the coatings obtained using various spray schemes was within the HV range of 2800 - 3500 MPa. Activation of EAS (AEAS) in a reducing atmosphere leads to the formation of dense coatings with a porosity of 2 - 5% and hardness $\text{HV} = 3000 \text{ MPa}$, characterized by low content of residual austenite ($V_\gamma \approx 20 \text{ vol}\%$)

and oxides. The lattice parameters of martensite and austenite are $a_{\alpha}=0.2875$ nm and $a_{\gamma}=0.3592$ nm, respectively. AEAS by a reactive jet with an excess of air provides the formation of a layer with a porosity of 2 - 5% and hardness $HV = 3500$ MPa, characterized by substantial content of oxidation products. The content of residual austenite in the coating is $V_{\gamma} \approx 20$ Vol. %. The lattice parameters of martensite and austenite are $a_{\alpha}=0.2875$ nm and $a_{\gamma}=0.3592$ nm, respectively. Coatings obtained by spraying with air had a hardness of $HV=3200$ MPa and a residual austenite content of $V_{\gamma} \approx 18$ vol% at the porosity 6–8%. The XRD data fixed the highest concentration of oxidation products in the coating after EAS with air. Lattice parameters were $a_{\alpha}=0.2875$ nm and $a_{\gamma}=0.3596$ nm for martensite and austenite, respectively.

The results of the study of the phase composition and hardness of coatings from powder wire FMI-2 indicate the influence of the deposition technique on the structure and properties of the layer obtained. A distinctive feature of deposited layers is the presence of an anomalously large amount of residual austenite (up to 30 vol%) and oxides. Generally, the content of residual austenite in hardened powder wire FMI-2 does not exceed 3 - 5 vol% [11-13].

One of the reasons for the appearance of the “austenitic effect” in coatings is a higher concentration of alloying elements (chromium and carbon) owing to the complete dissolution of chromium carbides during melting of the wire and saturation of the molten droplets with carbon from the propane flame. This is confirmed by the absence of $Cr_{23}C_6$ carbide particles in the coating. While analyzing the causes of austenite stabilization in the layer, one should keep in mind that under spraying surface layers are heated to 500–670 K. As a result, the sprayed coating undergoes isothermal aging at 520–670 K during its formation and cooling, which promotes thermal stabilization of austenite [1-7]. A factor that increases the stability of austenite in the sprayed layers is saturation of the molten droplets with carbon during melting and spraying with propane flame (Table 3).

Table 3

The influence of the composition of combustion mixture forming the spray on the carbon and oxygen contents in EAS coatings from powder wire FMI-2

Technique of spraying	Air/propane volume ratio in mixture	Oxygen content in coatings, %	Carbon content in coatings, %
1	(Gas flame) propane/oxygen ratio 1/4	1.3	0.6
2	(AEAS) 18	1.4	0.5
3	(AEAS) 30	2.2	0.4
4	(AEAS) clean air	3.3 – 3.5	0.4

The low velocity of molten steel particles and high concentration of carbon-containing propane in the combustion products contribute to a deeper saturation of molten droplets with carbon. These circumstances are associated with a high content of residual austenite in coatings obtained by the gas flame procedure (technique 1).

The smaller amount of austenite in coatings obtained by AEAS in the reducing atmosphere of the spray torch (technique 2) is due to the higher flight velocity of the molten particles, which is characteristic for this technique. In this case, the processes of diffusion saturation of the droplets with carbon from the reducing atmosphere of the products of propane/air mixture combustion do not have enough time to complete (flight time of molten droplets in the atmosphere of combustion products is not more than $5 \cdot 10^{-4}$ s), and the content of residual austenite in the layer decreases to ~ 20 vol%.

An increase in the oxygen concentration in the mixture is not accompanied by change in the amount of residual austenite in the coating obtained under conditions of supersonic velocities of molten particles (technique 3) and at relatively low particle velocities (technique 4). In both cases, the content of residual austenite in the layer does not exceed 20 vol%. The carried-out studies made it possible to conclude that for EAS there are such regimes and steels that can provide the formation of a large amount of metastable austenite in the coatings, which during the performance of the tribocoupling will turn into martensite. The experiments established a relation between the temperature of the beginning of martensitic transformation, T_M , for the wire material and the amount of metastable austenite formed in the resultant coating (Table 4) [1 -7].

In steels of group 1, as well as in corrosion-resistant martensitic steels, the temperature T_M is within 550 - 700 K. When spraying wires from these steels, the volume content of metastable austenite reaches 45%.

In the case of spraying wires from steels of the first two groups, the preservation of a large amount of metastable austenite can be prescribed to the high rate of crystallization of steel particles in the course of forming the sprayed layer and slowing down its cooling rate in the martensitic transformation region. The decrease in austenite stability in coatings from steels of the third group, sprayed over 2500 K, is explained by the effect of manganese and chromium contained in the steel on the temperature range of its martensitic transformation. Thus, a decrease in the manganese content from 5% to 1% leads to an increase in the temperature from 270 to 470 K [1-7]. In this regard, one of the possible ways to increase the T_M temperature is reduction in the chromium or manganese content in the austenitic phase of steels by oxidizing it during spraying.

Table 4

Metastable austenite content in EAS coatings obtained by spraying various steel grades

Group of steels	Steel grade	Temperature T_M , K	Temperature of heating under spraying, K	Content of austenite in coating Vol %
1	09G2S, 40KhN, 40Kh13 FMI-2	550–700	1700-2000 2100-2500 > 2600	25-45 17-20 < 6
2	9KhS, Kh12MF, 9Kh12, Kh6VF, 35KhNM, 40KhFVA, 65G	420–540	1700-2100 2200-2500 > 2500	15- 25 8 -12 < 6
3	08Kh18N10, 12Kh18N10T, 110G13	70–110	1700-2000 2000-2500 > 2500	95 - 98 90 - 95 90 - 95

Conclusions

The present work recommends to increase the wear resistance, corrosion resistance, and service life of parts *via* hardening and renovating them using combined EAS coatings characterized by high density, adhesion strength, and microhardness due to activation of the spraying process. It has been shown that by properly choosing design parameters and characteristics of equipment for EAS, it is possible to control the properties of restored surfaces in order to increase the service life of SMM parts. The right choice of equipment for spraying will allow one to increase the speed and temperature of the jet of spraying gas and molten particles, decrease the droplet diameter, increase the density, and reduce the oxidation of coatings. Moreover, the phase composition and microhardness of coatings obtained by spraying wires from austenitic and martensitic steel were investigated. The presence of an abnormally large amount of residual austenite (to 50 vol%) in coatings from martensitic steel was established. Studies of the resistance to fatigue failure showed that coatings deposited by EAS of wires provide a slight decrease in the fatigue strength limit to 10–13% (for comparison, coatings obtained by vibro-arc surfacing reduce the fatigue limit by 35–40%). In the course of tribological tests, the wear of sprayed coatings was established to be cyclical. The cyclicity of weight wear of sprayed coatings is associated with the degradation of their surface layer under friction, described in terms of physical mesomechanics of solids.

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Лопата О.В., Смирнов І.В., Головащук М.В., Лопата В.М. Дослідження властивостей покриттів, отриманих електродуговим напиленням

У роботі запропоновано підвищувати зносостійкість, корозійну стійкість та термін служби деталей машин та механізмів при їх зміцненні та реновації ЕДН-покриттями з високою щільністю, міцністю зчеплення та мікротвердістю за рахунок активації процесу напилення. У роботі розглянуто можливість за рахунок вибору конструктивних параметрів та характеристик обладнання для ЕДН керувати властивостями відновлених поверхонь з метою підвищення ресурсу деталей машин. Правильний вибір конструкції обладнання для напилення дозволить збільшити швидкість і температуру струменя газу і частинок, що транспортуються, зменшити діаметр крапель, підвищити щільність і знизити окислюваність покриттів. В роботі досліджено вплив факторів процесу напилення: витрат та тиску робочих газів, складу паливної суміші, дистанції напилення, дисперсності розпилення, матеріалу дроту та ін. на властивості ЕДН-покриттів.

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