THERMAL SPRAYING OF PSEUDO-ALLOY COATINGS (Review)

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The paper presents the experience in development and application of thermal spray pseudo-alloy coatings, and describes the principle of their formation. Characteristics of the most extensively used pseudo-alloy coatings and the effectiveness of their practical application in different engineering fields are given.

Keywords: *thermal spraying, electric arc spraying, composite coating, pseudo-alloy, pseudo-alloy coating, properties of coatings, practical application*

Development and application of new high-performance materials and technologies for repair, improvement of reliability and extension of service life of different-purpose assemblies and parts are a pressing task in the field of production of protective coatings.

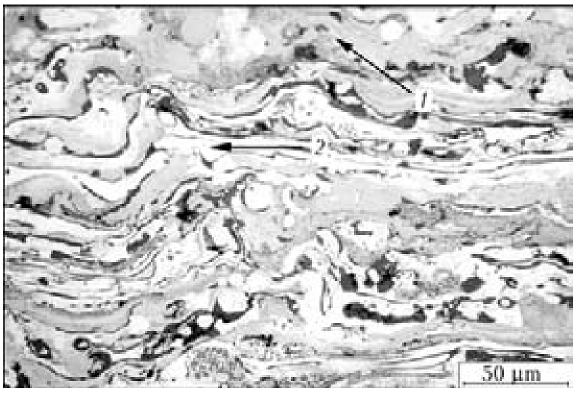
The composite coating is a heterophase coating formed in the process of its deposition, having a structure and properties typical of a composite material. Analysis of the process of thermal spraying, structure and physical-mechanical properties of the composite coatings reveals a number of advantages of such coatings and, in particular, their high strength, density, homogeneity and presence of phases with special properties [1].

Coatings with a pseudo-alloy structure are a separate type of composite coatings. They consist of materials that do not form solid solutions and compounds in the liquid and solid states (differing in melting temperatures and not fusing with each other). Owing to the absence of interaction between these materials in a wide range of concentrations and temperatures, the pseudo-alloy coatings combine the properties of each of their components. In the process of deposition of a multi-component coating particles of each of the deposited metals are preserved individually in a layer, although during metallising they were in the molten state. Such multi-component coatings are called the pseudo-alloy ones. Materials of the type of pseudo-alloys are characterised by a number of important properties, such as a combination of high values of melting and evaporation temperatures with mechanical strength, hardness, damping ability, wear resistance, self-lubrication ability under dry friction conditions, and a high level of electrical and thermal conductivity [2]. The required properties of pseudo-alloys are achieved by varying the ratio of their components. Properties of the pseudo-alloys strongly depend on the methods used to produce them: liquid- or solid-phase sintering, and impregnation.

At present the pseudo-alloys go in a wide range of compositions with different service properties. For example, the pseudo-alloys of the Ti–Mg (14–25 % Mg) system are characterised by good antifriction properties and corrosion resistance [3]. The pseudo-alloys of the Fe–Cu (15–25 % Cu) system feature a good ductility, strength and heat resistance. They are used to manufacture compressor blades, piston and sealing rings [3, 4]. Application of the pseudo-alloys of the Fe–Pb (10 % Pb, 2 % Sn, Fe — balance) system is attributed primarily to their good antifriction properties. They are used to manufacture sliding bearings [4]. The pseudo-alloys of the Fe–Mg (93 % Fe, 7 % Mg) system are used to manufacture consumable anodes for electrochemical protection of structural materials [3, 5]. The pseudo-alloys of the W–Cu, W–Ag, Mo–Cu, Mo–Ag and Ni–Ag systems are employed in electrical engineering as electrocontact materials and to manufacture plasmatron nozzles [6–10]. The pseudo-alloys of the Cu–Cr (35 % Cr) system are used to produce electric contacts for vacuum arc-extinguishing chambers [11].

Theoretical and experimental analyses showed the feasibility of preliminary calculation of physical properties of the composite materials (CM) and coatings, such as thermal expansion coefficient, thermal conductivity coefficient and elasticity modulus [12]. Based on the existing approaches to calculation of properties of CM, it is possible to make calculation-analytical estimation of the predictable properties of mechanical mixtures, where the thermal spray pseudo-alloy coatings belong to as to their structure. The latter consists of a mechanical homogeneous mixture of particles of the melt (splats) several micrometres thick and tens of micrometres in diameter, which were deformed at collision with the substrate surface. The Figure shows characteristic structure of the pseudo-alloy coating of the Cu–NiCr system.

The calculation method can be used to determine thermal conductivity coefficient λ_c [13], elasticity modulus E_c [11, 14] and thermal expansion coefficient α_c [11, 14] of the coatings:



Microstructure of Cu–NiCr system pseudo-alloy coating: *1* — Cu; *2* — NiCr

$$\lambda_c = \lambda_1 m_1 + \lambda_2 m_2,$$
$$E_c = E_1 V_1 + E_2 V_2,$$
$$\alpha_c = [\alpha_1 E_1 (1 - V_2) + \alpha_2 E_2 V_2] / [E_1 (1 - V_2) + E_2 V_2],$$

where λ_1 and λ_2 are the thermal conductivities of the coating components; m_1 and m_2 are the weight contents of the coating components; E_1 and E_2 are the elasticity moduli of the coating components; V_1 and V_2 are the volume contents of the coating components; and α_1 and α_2 are the thermal expansion coefficients of the coating components.

Coatings with the pseudo-alloy structure can be produced by the methods of electric spark alloying [15], ion-plasma magnetron sputtering [16] and thermal spraying (plasma and flame spraying, and arc metallising). The electric arc metallising method received the widest acceptance for deposition of the pseudo-alloy coatings.

Up to now no reference and regulation literature specifying service properties and technology for deposition of the pseudo-alloy electric arc coatings is available. Therefore, the purpose of this study is to establish and substantiate, on the basis of analytical review, the efficiency of application of electric arc deposition of the pseudo-alloy coatings in manufacture and repair of parts.

Equipment and consumables for thermal spraying of pseudo-alloy coatings. The following types of units were used to deposit the pseudo-alloy coatings:

- plasma spraying units UPU-3, UPU-4, UMP-5 and UMP-6 [17] (using powder consumables), as well as plasmatron UShR-2 [18];
- gas metallising devices of the MGI-2, MGI-5 [17], MGI-1-57 and GIM-2 types with extension head UG-2 [19];
- twin-wire devices for electric arc spraying — stationary (machine tool) devices EM-6, EM-12, EM-15, MES-1, and portable (manual) devices EM-3, REM-3A, EM-9, EM-10 and EM-14 [20];
- three-wire electric arc metallisers UMA-1 [21], three-wire heads MTG and three-phase devices TM-2 [22].

The three-wire electric arc metallisers (with motor drive EM-6 and attached three-wire head MTG) allow separate regulation of wire feed speeds [23].

The following powders are used for thermal spraying of the pseudo-alloy coatings:

- mechanical mixtures of components (Al–Sn [18]) conglomerated on some binder (mechanical mixture of powders of conglomerated Al–Ni and molybdenum [24]);
- composite powders consisting of a base core surrounded by a cladding layer of the second component (Al–Cu, Pb–Cu, Mo–Ni, Ag–Ni [24], Al–Mo [25]), the cladding layer being applied either by chemical deposition or vacuum evaporation.

The pseudo-alloy coatings can also be deposited by plasma spraying of powders produced by mechanical alloying (Cu–Ta [26], Fe–Cu [27], Mo–Cu [28]).

The pseudo-alloy coatings can be deposited with flame metallisers by using polymetallic wires that consist of two or three metals arranged in layers, which are produced by wrapping a wire of one metal with a strip of the other metal, and then their combined drawing through a die (aluminium-lead or copper-lead one) [29].

When using the twin- and three-wire electric arc devices to produce the pseudo-alloy coatings, a device is loaded with dissimilar wires, the diameters and feed speeds of which are selected on a base of the required proportion of coating components. The pseudo-alloy coatings are formed from a mixture of particles of dissimilar metals [23, 29]. Consumables in the form of solid wires (steel, aluminium, brass, zinc, lead, tin-lead) or flux-cored wires with a metal sheath (sheath of steels Sv-08, Sv-08G2S, 30KhGSA, steels 70, U8, U10, 20Kh13, 40Kh13 and 65G) and different core components are used for electric arc spraying of the pseudo-alloy coatings.

The antifriction pseudo-alloy coatings are produced from steel, copper, lead with an addition of aluminium, brass and other metals. The pseudo-alloy coatings on a steel base with copper, brass and aluminium, as well as steel-molybdenum coatings are applied to increase wear resistance [29]. The Zn–Al system coatings are used mainly for corrosion protection [19]. The content of the second metallic component in such coatings may be varied from 5 to 50 wt.%.

The process of thermal spraying of pseudo-alloy coatings. Thermal spraying allows producing pseudo-alloy coatings from non-fusing metals with the required properties and a wide range of combinations of their components. This technology can provide the pseudo-alloy coatings by using the alloy-forming components. A short time of contact of particles of the components (milliseconds) prevents development of the interaction processes.

In combined spraying by the method of electric arc metallising of metals characterised by some mutual solubility or capable of entering into chemical interaction, structure of the pseudo-alloy coatings is characterised by the presence of different-concentration solid solutions or intermetallic phases. An example is a pseudo-alloy coating of the Al–Cu system [30]. In case of combined spraying of metals characterised by low mutual solubility, the oxidised particles of the initial metals are detected in structure of the pseudo-alloy coatings. Such coatings include Cu–Pb and Cu–steel.

High antifriction properties of the pseudo-alloy coatings are attributable to their specific structure. Characteristic features of the pseudo-alloy coatings are heterogeneity and microporosity. The heterogeneous structure and presence of developed roughness and porosity (8–12 vol.%) on the layer surface provide favourable conditions for preservation of oil film during the friction process even after termination of feeding of a lubricant.

Mechanical properties of the pseudo-alloy coatings are related to their structure and depend on the process parameters that change the quantity and form of location of oxides, as well as sizes and shapes of particles [31]. For instance, increasing the air pressure in electric arc spraying makes it possible to achieve a finer-grained structure of the layer, but causes considerable oxidation of a coating material. Also, the spraying distance has a strong effect on physical-mechanical properties of the coatings. With a 25 to 300 mm increase in the spraying distance the degree of oxidation of the spraying particles grows and the amount of oxides in the layer increases from 10 to 40 %. Moreover, the particles reach the substrate surface in a more cooled state, this causing a decrease in strength properties of the coatings (tensile and compressive strength — by 40 %, hardness — by 5–10 %) [31].

Physical-mechanical properties of the pseudo-alloy coatings can be improved by heat treatment, which is used for the pseudo-alloy coatings consisting entirely of refractory metals or containing them in the dominating amounts, as well as coatings of non-ferrous pseudo-alloys. The latter (MS25, M75 POS30) after heat treatment have improved running-in ability [19]. If dissimilar materials are used in the arc device as anode and cathode, the question arises of analysis of the character of formation of a spraying material jet in simultaneous spraying of two wires (whether they can interact between each other during the spraying process). Study [32] presents analysis of the particles produced by simultaneous spraying of steel and copper wires by using the electric arc device. Copper and iron are almost insoluble, and this may cause difficulties with formation of solid solution between them. In addition, at the initial stage of melting and detachment of a drop from the tips of the two wires they have a low possibility of contact because of the effect of a spraying gas flow. Meanwhile, after spraying and in flight the particles may enter into contact with each other. However, as shown by analysis, contact interaction and solubility of the two materials are insignificant (an iron particle contains 1.27 wt.% Cu, and a copper particle contains 1.9 wt.% Fe).

The technology for deposition of the pseudo-alloy coatings has some drawbacks related to violation of stability of the electric arc metallising process because of different melting rates of wires with different compositions. To eliminate them, it is necessary to work out special measures (using wires of different diameters or feeding them with different speeds, removal of oxide film from the wires), this making the technological process more complicated and limiting the possibility of regulation of composition of the coatings.

Spraying parameters, structure and properties of thermal spray pseudo-alloy coatings. *Antifriction pseudo-alloy coatings*. The pseudo-alloy coatings produced by electric arc spraying and used as antifriction materials in sliding friction units have a number of advantages. Similar to cermet materials, their structure consists of particles of metals, oxides, nitrides, pores etc. The pseudo-alloy coatings can be well and quickly run-in and exhibit a lower susceptibility to scores, compared to other antifriction coatings [33].

Compositions of the most extensively used antifriction pseudo-alloy coatings and some data characterising their properties [29] are given in Table 1.

Parameters of spraying of the pseudo-alloy coatings using electric arc devices EM-3A are given in Table 2 [29].

Parameters given in Table 3 are recommended for spraying of the pseudo-alloy coatings using electric arc device EM-6 with three-wire head MTG [23].

Table 4 gives parameters for spraying of the pseudo-alloy coatings by the flame method [29].

Table 5 gives values of physical-mechanical properties of the pseudo-alloy coatings (under liquid friction conditions) produced by electric arc metallising using device EM-3A [19].

The Cu–Pb system pseudo-alloy coatings deposited by using the three-wire metalliser have characteristic laminated structure [30]. Peculiarity of structure of these pseudo-alloy coatings is their porosity. Specific structure and character of adhesion between the particles of the Cu–Pb system coatings are attributable to relatively low values of their physical-mechanical properties, which can be increased by annealing to sintering in a reducing environment. The concentration of absorbed oxygen and porosity of the coatings reach minimal values, and laminated structure fully vanishes in 3 h at an annealing temperature of 900–940 °C in the 10–15 % mixture of charcoal and aluminium oxide. This change of structure of the Cu–Pb system pseudo-alloy coatings leads to a considerable improvement of their wear resistance.

Independently of the surface preparation method, annealing provides a substantial decrease in strength of adhesion of the pseudo-alloy coating to the substrate. In case of deposition of the Cu–Pb system coating on the steel substrate prepared by cutting a ragged thread, the adhesion strength after annealing decreased to 3.8–4.6 MPa, compared to 10–15 MPa before annealing, because of formation of the intermediate film of the copper and iron oxide mixture, i.e. Cu_2O, FeO and Fe_3O_4. This led to the necessity to exclude direct chemical interaction between the pseudo-alloy coating components and steel by depositing a protective sub-layer of tin, brass, nickel or copper. Appli-

Table 1. Antifriction pseudo-alloy coatings and their properties

Pseudo-alloy coating	Composition, %	Brinell hardness under 250 kg load	Oil absorbability, %	Running-in compared to babbit metal B83, %	Ultimate load·10^{-4}, N/m^2, at sliding speed, m/s	
					1	4
Al–steel (AZh50)	Al 48–50 Fe 50–52	37–44	10–14	58	1030	1079
Cu–steel (MZh50)	Cu 45–50 Fe 50–55	–	–	64	883	1128
Cu–steel (MZh75)	Cu 25–30 Fe 70–75	95–107	3.0–3.2	80	668	785
Brass–steel (LZh75)	Cu 17–20 Zn 8–10 Fe 70–75	95–107	2.5–3.0	42	490	834
Cu–Pb (MS25)	Pb 25–30 Cu 70–75	35–37	–	47	1030	1373
Same after heat treatment	Pb 25–30 Cu 70–75	24–27	–	75	1962	2158
Cu–Sn–Pb (M75, POS30)	Sn 2–3 Pb 6–7 Cu 90–91	25–28	–	80	1570	1619
Al–Pb (AS50)	Al 48–50 Pb 50–52	33–34	5.2	—	1760	1962

Table 2. Parameters of spraying of pseudo-alloy coatings by using electric arc devices EM-3A

Pseudo-alloy coating	Compressed air pressure·10^{-4}, Pa	Electrode voltage, V	Productivity of device, kg/h	Distance from nozzle to workpiece surface, mm
Al–steel (AZh50)	49–59	20–40	2.0–2.4	100–125
Cu–steel (MZh75)	59–69	30–40	4.0–8.0	125–150
Brass–steel (LZh75)	49–59	30–40	4.0–8.0	125–150
Al–Pb (AS50)	49–59	20–30	2.0–2.4	75–100

cation of the copper sub-layer allowed the adhesion strength of the Cu–Pb system coating after annealing to be increased 3 to 4 times (Table 6) [30].

It was found that the annealed pseudo-alloy coating with a 25–30 % Pb content is optimal in a combination of physical-mechanical and antifriction properties, adhesion strength, wear resistance and composition [30]. Structure of the pseudo-alloy coatings is a mixture of lamellae of the steel and copper particles with oxides and pores located along their boundaries. The reason for using the Cu–steel system pseudo-alloy coatings as a bearing material is heterogeneity of their structure and possibility of producing them from inexpensive metals. It was shown that the Cu–steel system pseudo-alloy coatings are characterised by a higher wear resistance than steel coatings (see Table 5). The Cu–steel pseudo-alloy coatings containing 10–30 % Cu can be easily run-in, and can operate under conditions of substantial loads, low temperatures and low friction coefficient. A drawback of the Cu–steel system pseudo-alloy coatings is that they are hard to machine, and scrape in particular, because of the oxide and nitride inclusions characterised by an

Table 3. Parameters of spraying of pseudo-alloy coatings by using three-wire device (2 mm wire diameter, 20–40 V voltage)

Coating material	Content of element, wt.%	Wire feed speed, m/min	Current in each phase, A	Productivity of device, kg/h
Steel	75	1.0–2.0	50–125	4.0–8.0
Copper	25	0.6–1.2	75–150	
Steel	75	1.0–2.0	75–150	4.0–8.0
Brass	25	0.6–1.2	60–110	
Aluminium	50	1.0–2.0	40–90	2.0–4.0
Lead	50	0.5–1.0	15–30	
Aluminium	30	1.0–1.2	90–110	3.0–3.6
Steel	70	1.3–1.6	40–60	
Aluminium	50	1.0–1.2	90–110	2.0–2.4
Steel	50	0.70–0.85	50–80	

Table 4. Parameters of flame spraying of pseudo-alloy coatings (1.5 mm wire diameter)

Pseudo-alloy coating	Productivity of device MGI-1-57, kg/h	Pressure, Pa	
		Oxygen	Fuel gas
Cu–Pb (MS25)	0.50–0.60	(2.5–5.0)·10^5	(0.35–0.75)·10^4
Al–Pb (AS50)	0.45–0.90	(2.5–5.0)·10^5	(0.35–0.75)·10^4

Table 5. Physical-mechanical properties of pseudo-alloy coatings under liquid friction conditions

Pseudo-alloy coating	Friction coefficient, MPa, at v = 1–4 m/s for specific pressure				Running-in ability*	Brinell hardness at P = 250 kg, δ = 5 mm	Oil absorbability, %
	50	100	150	200			
Al–steel (AZh50)	0.0049–0.0061	0.0045–0.0053	–	–	0.58	37–44	10–14
Cu–steel (MZh50)	0.0056–0.0063	0.0035–0.0036	–	–	0.64	–	–
Cu–Pb (MS25)	0.0044	0.0037–0.0042	–	–	0.47	35–37	–
Cu–Pb (MS25) (heat treatment)	0.0039–0.0045	0.0033	0.0030–0.0033	0.0032–0.0037	0.75	24–27	–
Cu–Sn–Pb (M75, POS30) (heat treatment)	0.0039–0.0047	0.0033–0.0035	0.0028–0.0041	–	0.80	25–28	–
Al–Pb (AS50)	–	–	–	0.0041	–	33–34	5.2
Cu–steel (MZh75)	0.0056–0.0061	–	–	–	0.80	95–107	3.0–3.2
Brass–steel (LZh75)	0.0065–0.0072	–	–	–	0.42	95–107	2.5–3.0
Steel (Zh100)	0.0070–0.0133	–	–	–	0.73	107	1.8–2.0

*Running-in ability of babbit metal of the B83 grade was assumed to be equal to 1.

increased hardness. It was suggested that to improve properties of the Cu–steel coatings they should be subjected to heat treatment (annealing and normalising), which leads to a change in shape of the oxide particles and decrease in hardness of the coatings from 1850 to 125 MPa [30].

The Cu–Al system pseudo-alloy coatings produced by flame spraying differ greatly in their structure and oxide content from those produced by the electric arc metallising method, as the latter causes overheating of the initial metal particles. In flame spraying the temperature of the molten particles corresponds to the liquidus curve. Because of this and owing to a substantial concentration of the combustion products in the gas flow, the melt is not much subjected to intensive oxygen saturation [30].

Wear-resistant pseudo-alloy coatings. The mechanism of formation and structural peculiarities of the steel 65G–Al system electric-arc coatings were investigated in study [34]. In simultaneous spraying of electrode wires of steel 65G and aluminium, all the intermediate phases forming in interaction of iron with aluminium both in the solid and molten states were fixed in structure of the products. The optimal combination of properties (moderate microhardness and sufficient ductility) determined by the corresponding composition of intermetallics was noted in the coatings with the 10 % Al content.

Spraying of the steel-aluminium pseudo-alloy coatings with a content of steel in the spraying material equal to 50–65 wt.%, and their subsequent pressure treatment involving compression provide the optimal structure of the coatings consisting of a hard reinforcement (hard particles of intermetallics formed in spraying of a coating) and a soft matrix (aluminium, steel), as well as plastic deformation of the soft component achieved during compression as a result of separation of oxide films from its particles. The stresses leading to separation of the oxide films from the surface of the particles increase with growth of the content of steel in the pseudo-alloy layer. Separation of the oxide films leads to increase in cohesion strength of a coating, thus resulting in a considerable increase in its wear resistance and, hence, extension of service life of the coated parts [35].

The method is available for production of composite electric arc coatings from two dissimilar electrode materials, one of which being a low-carbon mild steel with a hardness not in excess of 1500 MPa. Flux-cored wire of the Fe–Cr–B–C alloying system is used as a second wire [36]. This method is employed to produce coatings based on a combination of commercial flux-cored wires of the Fe–Cr–B–C system (PP-AN-307) and all-drawn wires Sv-08 for repair of machine parts, whose friction surfaces operate under boundary friction and abrasive wear conditions. Increased wear resistance is attributed to the presence in a coating of a large amount of oxygen, iron and boron oxides, which provide a low level of the friction coefficient, whereas the presence of borides Fe_2B in the coating favours its high wear resistance. It was established that under the abrasive wear conditions using a fixed abrasive the value of wear resistance of the composite PP-AN-307 + Sv-08 coatings is 2.1 times higher than that of the similar coatings of flux-cored wire AN-307, and 1.4 times higher than that of steel ShKh-15 [37].

Corrosion-resistant pseudo-alloy coatings. Protection from water and atmospheric-water corrosion can be provided by using the Zn–Al (1:1) system pseudo-alloy coatings. Wetting parts with the Zn–Al coatings by water causes intensive oxidation of zinc, while oxides plug up the coating pores, thus preventing the access of water to the base metal [19].

Study [38] reports investigations of corrosion properties of the Zn–Al system coatings produced by the electric arc method with simultaneous zinc and alu-

Table 6. Adhesion strength of Cu–Pb system coating deposited on copper-plated low-carbon steel, MPa

Lead content of coating, wt.%	Before annealing	After annealing
0	13.0	35.0
10	11.2	34.0
30	7.8	32.0
50	6.2	17.5

minium wire spraying, as well as spraying of the zinc and flux-cored wires Al–5 wt.% Mg. The 3.5 % solution of sodium chloride was used for the tests. As shown by the investigations, the Zn–Al pseudo-alloy coatings have a 3 times higher corrosion resistance than the zinc or aluminium wire coatings, while the Al–Mg–Zn system pseudo-alloy coatings (73 % Zn–25.6 % Al–1.4 % Mg and 86 % Zn–13.3 % Al–0.7 % Mg) have a 1.25 times higher corrosion resistance than the Zn–Al system pseudo-alloy coatings.

Experience in practical application of thermal spray pseudo-alloy coatings. Antifriction pseudo-alloy coatings feature a good and quick running-in ability and exhibit a lower susceptibility to scores compared to other antifriction coatings. The heat-treated Al–steel, Cu–steel, Cu–Pb, Cu–Sn–Pb and Al–Pb system pseudo-alloy coatings can be applied instead of tin and tin-free brasses and babbit metals over the acceptable ranges of loads and speeds under static loads for non-split bushings, reducing gears, transmissions, cranes, machine tool equipment, metal-cutting machine tools, ventilators, smoke exhausters, compressors and centrifugal pumps operating in pair with quenched and non-quenched necks [19].

Application of the Cu–Pb coatings as an antifriction material is efficient for the internal surfaces of steel bushings [30].

The Cu–Al coating with the 20 wt.% Cu content is recommended for sliding bearings operating in assemblies of metal-cutting equipment and hoisting devices [30].

Study [39] presents the investigation results on development of wear-resistant coatings for strengthening and repair of hubs of guide vanes of centrifugal pumps of the ETsN type. The 20Kh13 + AMg coating composition produced by spraying of the 1.6 mm diameter wires at the same feed speed was tried out as one of the variants of the coatings.

Thermal conductivity of these coatings is markedly higher than that of steel 12Kh13, which should affect the calorific intensity at the point of contact of the interacting surfaces. Good results on all of the investigated parameters were also exhibited by the 12Kh13 + 08G2S coating produced from the 1.6 and 1.2–1.4 mm diameter wires. It has a ferritic-pearlitic and martensitic structure with a small amount of carbides, features sufficient density (porosity — 6–7 %), and consists of a layer of structural components uniformly distributed in the bulk. The coating can be easily machined by cutting even at a speed of up to 6 m/s (600 rpm). The content of chromium in such coatings decreases to some extent and is equal to about 8 %. Nevertheless, they are characterised by satisfactory corrosion resistance and comparatively high wear resistance [39].

The steel–Al pseudo-alloy coatings are sprayed on the surfaces of pistons by the electric arc method to increase their wear resistance. To improve quality of a coating, prior to deposition of the pseudo-alloy layer an aluminium sub-layer is sprayed on it, which can be easily deformed under the effect of shrinkage stresses induced in the steel-aluminium pseudo-alloy applied to it, thus preventing cracking and favouring increase in the coating to substrate adhesion strength [40].

Study [41] describes the electric arc coatings for piston compression rings of marine medium-reverse engines. These coatings consist of the steel–bronze (60S2-Br.KMts) pseudo-alloy with high tribotechnical and adhesion properties. It was established based on the results of comparative tribotechnical tests that in operation of the 60S2-Br.KMts-3-1 pseudo-alloy coating in pair with the cylinder bushing material (SCh 25) the consumption of power for overcoming the friction forces decreases to 20 %. Moreover, growth of wear resistance of the piston ring material (more than 5 times) and cylinder bushing (3 times) is fixed, this providing extension of the inter-repair period without disassembling. A substantial increase (by 50 % for score load) in score resistance of the tribo-coupling is noted.

In study [42] the steel–Mo pseudo-alloy coatings were deposited by the twin-wire metallising method with an independent feed of the molybdenum and steel wires on piston rings of a cylinder diesel locomotive. The rings with the coatings were removed and investigated after 4000 h of operation. Investigation of the degree of wear after operation showed that in the case of coating the rings with electrolytic chromium the wear was higher compared to the pseudo-alloy coating. Examinations of the wear surface indicated that wear was mostly of the abrasive type. Increase in hardness compared to the initial state was noted for the molybdenum component of the layer in all the rings after operation. Also, increase in hardness for the steel particles in a range of *HV* 5000–6000 MPa compared to the initial state, as well as disappearance of the particles with hardness of *HV* 3000–4000 MPa were fixed. The offered technology for thermal spraying of coatings provides extension of service life of the piston rings and other parts operating under wear conditions, and can be employed to improve reliability and durability of parts experiencing substantial wear during operation.

CONCLUSIONS

1. The most common method for production of pseudo-alloy coatings is electric arc spraying, as it is charac-

terised by high productivity and practicability. Thickness of the deposited layer can be varied from 50–100 μm to 3–6 mm or more. Composition of the coatings is regulated by changing diameters of the wires and their feed speeds.

2. The data presented on practical application of the pseudo-alloy coatings indicate that the metallised pseudo-alloy coatings are efficient as antifriction, wear- and corrosion-resistant materials.

3. Antifriction pseudo-alloy coatings are applied in manufacture of sliding bearings instead of bronzes and babbit metals to improve performance of parts under the abrasive wear conditions both in primary strengthening and in repair of parts. The Zn–Al pseudo-alloy coatings are used for corrosion protection of pipelines, tanks, vessels, metal structures of feed-processing shops of cattle-breeding complexes and agrochemical equipment.

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