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Characteristic Features of Structure and Analysis of Friction Behavior of Electric-Spark Coatings from Powder Wires

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ABSTRACT

The structure, phase and chemical composition of electric-spark coatings (ESC) obtained on the *Elitron* installation from powder electrode wires were investigated using a *Neophot-2* optical computer microscope, an EVO-40XVP (Carl Zeiss) scanning electron microscope, DRON-3.0 X-ray diffractometer, EXPERT 02L elemental composition analyzer. The structure of the ESC is an austenitic matrix with boride inclusions (Fe,Cr)B, iron boride Fe_2B, chromium borides of iron $Cr_{1.65}Fe_{0.35}B_{0.96.}$ The distribution of Cr, Fe and C in these coatings is uneven and varies in wide range. The micromechanical characteristics of the modified surface layer of steel 45 were analyzed using Ultra Nano Hardness Tester and Nan Scratch Tester. The article provides an analysis of the frictional behavior of the ESC under conditions of dry friction and boundary lubrication according to the finger-disc scheme. Frictional stability of such coatings indicates the expediency of using electric-spark alloying (ESA) technology with powder wires (PW) and powder wires with graphite (PWG) to increase the service life of both machine parts and cutting tools.

Keywords: powder wire, electric-spark coating, micromechanical characteristics, spectral analysis, phase analysis, frictional behavior, dry friction, wear resistance.

INTRODUCTION

Over the past decades, powder wires (PW) have been widely used in the application of restorative and protective coatings to extend the service life of machine parts, mechanisms, and technological equipment. PWs of various metal systems are most often used to obtain wear-resistant and restorative gas-thermal coatings, in this case, metal systems can be conditionally divided into the following groups [1, 2]:

a) WC-Co, WC-Co-Cr, WC-Ni, the object of application of which in the aerospace industry are the parts of hydraulic systems; in the automotive industry – protection of cylinder liners (sleeves) against blocking; in turbine construction – rotating shafts; in shipbuilding – protection of water turbines against erosion and corrosion.
b) Ni-Al, Cu-Ni-In: in the aerospace industry – sub-layers of coatings; imparting anti-fretting properties.
c) Cr_3C_2-Ni-Cr: in the aerospace industry – sealing at high temperatures; in turbine construction – high-temperature parts of turbine sections.
d) Co-Cr-Si-Mo: in turbine construction – protection of compressor parts.
e) Ni-Cr, Ni-Cr-Mo, Ni-Mo-Al: in the automotive industry – restoration of crankshafts; in turbine construction – building up and repair of parts.
f) Mo – in the automotive industry: protection against drop impingement erosion.

The application of coatings of the WC-9Co-4Cr powder system is performed by high-speed procedures of thermal spraying, using the methods of detonation, supersonic air-gas plasma spraying (SAGP) and supersonic oxy-fuel gas spraying (HVOF) [3–7]. These spraying methods allow the formation of dense coatings consisting of inclusions of tungsten carbide uniformly distributed in the Co-Cr matrix. The porosity of the coatings does not exceed 1%, the microhardness is 11.0–11.7 GPa, which is higher than the microhardness of the galvanic chromium coating (10 GPa). The microhardness of the detonation coating is lower and amounts to 8.5 GPa, which is due to a partial loss of carbon and the appearance of oxide inclusions in the coating owing to the presence of an oxidizing medium of the detonation products. In terms of characteristics such as hardness, adhesion strength (more than 50 MPa) and porosity, these coatings have an advantage over galvanic chromium plating. Among other methods of high-speed gas thermal spraying of the coating of the WC-9Co-4Cr system, the SAGP method is characterized by the highest efficiency (15 kg/h).

In order to reduce the cost of the spraying process, work is constantly underway to develop tungsten-free PWs, which would not be inferior in tribotechnical characteristics to a tungsten-containing coating. In particular, the fact of increasing the abrasive wear resistance of coatings from PW of the Fe-Cr system [8], the Fe-B system [9], the Fe-Cr-B and Fe-Cr-B-C systems [10] was established, the structure and physical-and-mechanical properties of such coatings have been studied. The tribological characteristics of amorphized gas-flame coatings [11] have been defined for PW of the Fe-B system.

The PW of the Fe-Cr-C system [12] and the PW for the electric arc spraying of the PhMI series based on the Fe-Cr-B-Al system [13–15] have been widely used. High wear resistance and efficiency of coatings during machining are provided when the hardness of HV 300…400 with a minimum amount of the oxide phase in the structure is reached. The minimum amount of oxygen in the coatings at the level of 2 wt.% is provided in the presence of 0.8% carbon, 6% chromium, and 6% aluminum in the PW charge. With an increase in the aluminum content in the coating, the amount of martensite decreases, but the content of ferrite increases. In this case, the hardness of the coating decreases with a simultaneous increase in the adhesion strength. The optimum hardness of the coating in the range of HV 300–400 is ensured when the PW contains 6–12 wt.% aluminum. The matrix phase of such coatings is ferrite alloyed with chromium and aluminum. Depending on the ratio of alloying elements, the coating of the Fe-Cr-B-Al system has a hardness of HV 650, the hardness of the Fe-Cr-Al-Mn-Mo-Si system is HV 350, the hardness of the Fe-Cr-B-Al-Ni system is HV 1000, the hardness of the Fe-Cr-B-Al-W system is HV 1150, the hardness of the Fe-Cr-Al-Mn-Mo-Ti system is HV 500. It is found that with an increase in the hardness of coatings up to HV 700–800, their wear resistance increases, and more than HV 800 – decreases, which is associated with the occurrence of microcracks in the coatings. Coatings based on the Fe-Cr-B-Al system of the PhMI brands provide an increase in wear resistance under conditions of abrasive wear by a factor of 3.5–7.

The physical-chemical processes occurring during the formation of particles of iron intermetallics based on Fe_3Al alloyed with Cr, Zr, Mg, La, and Ti under conditions of mechanochemical synthesis were studied in works [16, 17]. It was found that the mechanism of formation of both unalloyed Fe_3Al particles and particles of alloyed powders based on this intermetallic compound consists of a number of successive stages: formation of conglomerates from a mixture of initial Fe powders and aluminum alloys; formation of solid solutions of alloying elements based on the Fe_3Al lattice or an Al solid solution in the FeTi lattice; transformation of solid solutions into single-phase products $Fe_3Al(Cr,Zr)$, $Fe_3Al(Mg)$, $Fe_3Al(Mg,La)$ and $(Fe,Ti)_3Al$ with nanodispersed structure (coherent scattering region 10–30 nm). Doping of the Fe_3Al alloy with magnesium, lanthanum and especially with titanium contributes to an increase in its microhardness in accordance with 5.3 GPa, 5.6 GPa, 7.8 GPa.

The influence of carboboride-based fillers on the mechanical properties of coatings is considered in works [18, 19]. It was found that the interaction of the ferrite shell of the wire with fillers of B_4C and B_4C with the addition of nanocrystalline ZrO_2 powder results in the formation of iron borides alloyed with carbon, and the ferrite matrix contains boride and carboboride eutectics. The average microhardness of the carboborides and the matrix is 17.78 GPa and 16.40 GPa for B_4C and 8.69 GPa, and 9.95 GPa for $B_4C + ZrO_2$. The addition of 0.5% nanopowder ZrO_2 accelerates the reactions of forming dispersed iron borides, promotes their uniform distribution in the structure and increases the microhardness of the coating up to 7.0 GPa.

The paper gives much attention to the study of using PW of the Fe-Mn-B-C system for the application of wear-resistant eutectic coatings [20–22]. A positive effect on resistance to abrasive wear and wear resistance under conditions of boundary lubrication was revealed when applying electric arc coatings from PW of the Fe-Cr-C and Fe-Cr-B-Al systems, as well as the effect of laser infusion of such coatings to improve their tribological characteristics [23].

However, the use of powder wires for electric-spark alloying (ESA) technology is hardly covered. There is no data on the wear resistance of the electric-spark coatings (ESC) applied by the powder wire (flux-cored wire) electrode. Therefore, the study of the structure of such coatings and the analysis of their frictional behavior under conditions of friction and wear is important for tribomaterials knowledge.

The aim of the article is an investigation of structure, phase and chemical composition of ESC from powder electrode wires, its micromechanical characteristics, frictional behavior under conditions of dry friction and boundary lubrication.

METHODS

The application of ESC was carried out on the Elitron installation for ESA produced by the research plant Institute of Applied Physics of the Academy of Sciences of Moldova, which consists of a generator and a manual vibrator using alloying mode 9. The diameter of the electrodes was 3.2 mm. The paper considers two types of ESC: applied in one pass with powder wire (PW), the second type – one pass with PW and the second pass with powder wires with graphite MPG-7 (PWG). The choice of the serial powder wire (80X20R3T) of the Fe-Cr-B-C system is due to its widespread use for the restoration of worn-out surfaces by surfacing, low cost and satisfactory wear resistance of the deposited surface of the product.

ESC metallographic studies were performed on a Neophot-2 optical computer microscope. Sections of steel 45 with applied ESC were made by grinding on sand paper with a grain size of 350; 500; 1000; 1500 μm, after which the polishing was carried out on Struers Labopol-5 polishing machines using diamond pastes of various grain sizes: 60/40; 40/28; 28/20; 20/14; 14/10; 10/7: 7/5; 5/3; and 3/2 μm. The final stage of polishing was performed on a woolen substrate using diamond paste 2/1 and 1/1 μm.

ESC spectral analysis. The microstructure and chemical composition of the deposit on the surface of steel 45 was studied using an EVO-40XVP (Carl Zeiss) scanning electron microscope. An image of the modified steel surface was obtained by registering secondary electrons by scanning with an electron beam with an energy of 20 keV. To determine the chemical composition, the method of X-ray spectral microanalysis was applied which was implemented in the system of the above-mentioned INCA Energy 350 scanning electron microscope. Spectral analysis of characteristic X-ray radiation excited by a primary electron beam with an accelerating voltage of 15 kV was carried out using energy dispersion EDX (Energy Dispersive X-ray spectroscopy).

The phase composition of surface layers on specimens measuring 10×10×2 mm was identified by X-ray phase analysis on a *DRON-3.0* X-ray diffractometer (focusing according to the Bragg-Brentano scheme, CuK_α – radiation (λ_α = 1.54056 Å). The voltage at the anode of the X-ray tube was 30 kV at a current of 20 mA. The scanning was performed in the range 2θ = 20–90° with a step of 0.05°. The calculation time step was 5 s. The software packages Sietronix and Powder Cell 2.4 were used, with the help of which the Fourier processing of the diffractograms was carried out, the locations of the diffraction maxima of the reflection were determined, identified according to JSPDS-ASTM phase file data.

The chemical composition of the surface layers was determined by X-ray fluorescence analysis using an EXPERT 02L elemental composition analyzer at a voltage of 40 kV at a current of 50 μA.

RESULTS

The microstructure of the ESC from powder wire PW and PWG is shown in Figure 1. The thickness of the coatings on the surface of steel 45 is in the range of 40–60 μm. Based on the tests on nanoidentation of the studied ESC employing the Ultra Nano Hardness Tester

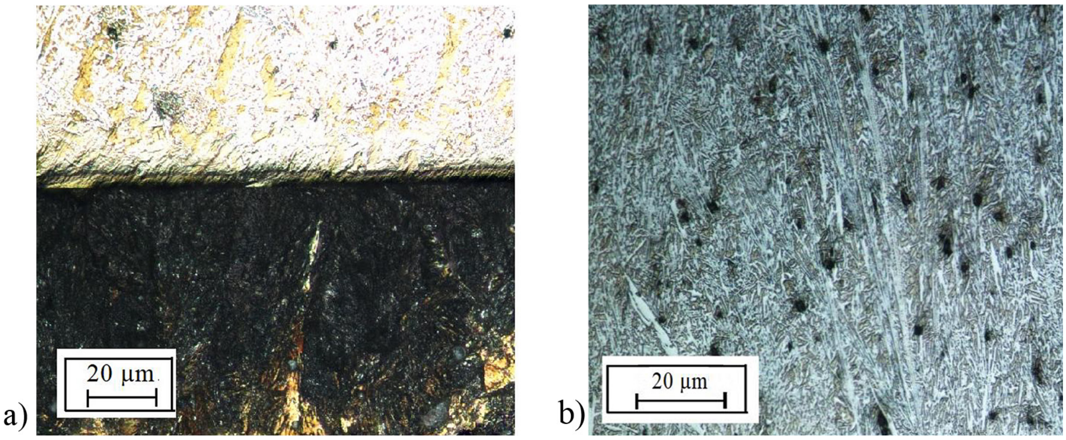

Fig. 1. Microstructure of electric-spark coating obtained by the PW (a) and PWG (b) electrodes, x200

(UNHT) using the Berkovych diamond indenter and nano-scratching employing the Nan Scratch Tester (NST) CSM Instruments device, which is equipped with a rod with a tip in the form of a spheroconical diamond indenter with a radius of 2 µм, a noticeable difference [24] in the micro- and submicrovolumes of the ESC surface layer was established, depending on the alloying with a PW electrode and a PWG electrode; the indicator values using the latter are significantly higher. Thus, the hardness of the coating with PWG is 24% higher than with PW ($HV_{0,02}$ 2311 vs. $HV_{0,02}$ 1710). Creep (0.97 vs. 0.86%), relaxation ability (0.51 vs. 0.45%), Young's modulus (207.86 vs. 180.95 GPa) increase, which leads to an increase in strength. At the same time, there is a decrease in plastic deformation work A_{pl} (4127.42 vs. 5168.76 pJ) and contact stiffness (0.3146 vs. 0.3254 mN/nm), which indicates an increase in microplasticity.

As an example, Table 1 shows the concentration values of chemical elements for one of the ESC spectra obtained from PW and PWG powder wires, and Fig. 2 shows their graphical interpretation.

It should be noted that in the ESC from powder wires of the Fe-Cr-B-C system, the distribution of chromium, iron and carbon is rather uneven and varies for all studied spectra within a fairly wide range (excluding boron). A number of other elements are identified (see Table 2).

PW and PWG powder wires have approximately the same percentage content of chemical elements. In PWG, three times more C is expected due to graphite. As a result, the percentage of Fe decreased by two times. Traces of Ti and K

Table 1. Weight and atomic content of chemical elements (for Fig. 2)

Powder wire					
PW			PWG		
Elements	Weiqht, %	Atomic, %	Elements	Weiqht, %	Atomic, %
BK	6.70	13.67	BK	4.60	8.31
CK	22.64	41.56	CK	40.21	65.38
OK	15.63	21.55	OK	6.40	7.82
AlK	2.52	2.06	MgK	0.32	0.26
KK	0.13	0.08	AlK	1.70	1.23
TiK	0.15	0.07	SiK	0.75	0.52
CrK	13.92	5.91	CaK	0.77	0.37
MnK	0.32	0.13	CrK	13.59	5.10
FeK	37.71	14.89	MnK	0.34	0.12
ZnK	0.27	0.09	FeK	29.93	10.47
Total	100.00		CuK	0.48	0.15
			ZnK	0.90	0.27
			Total	100.00	

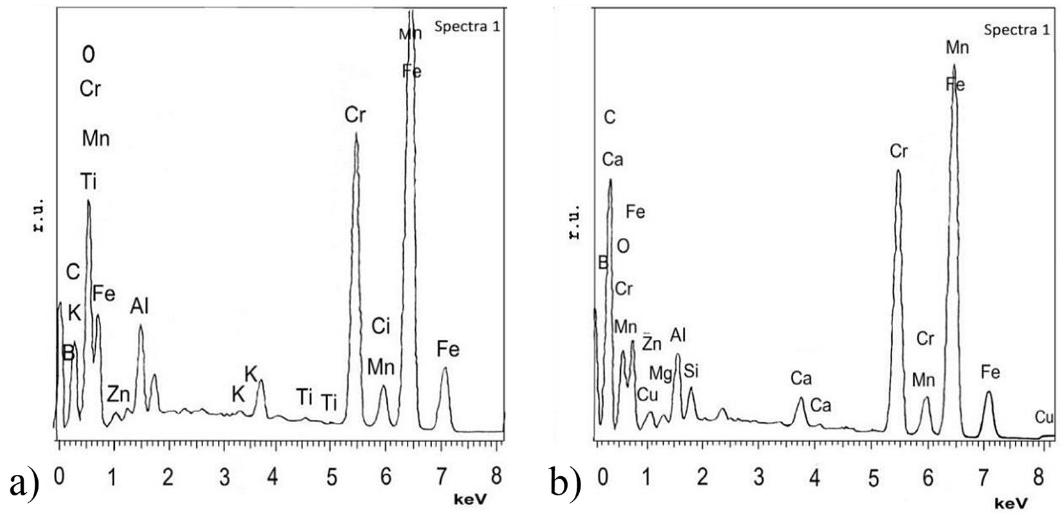

Fig. 2. Graphical interpretation of the chemical elements content in the ESC obtained from PW (a) and PWG (b)

were found in PW, and traces of Mg, Ca, Cu – in PWG. The distribution of carbon, chromium, iron, boron, titanium and oxygen in the ESC from PWG is shown in Figure 3.

X-ray phase analysis (Fig. 4) showed that the matrix phase of the ESC, obtained from both PW and PWG is a solid solution based on iron Fe (110). Both ESCs contain boride inclusions (Fe,Cr)B, as well as Fe (211). In addition, ESC from PW contains Fe_2B and iron Fe (200), while ESC from PWG contains boron B (122) and chromium iron borides $Cr_{1.65}Fe_{0.35}B_{0.96}$ (131) and (511).

Wear resistance of steel 45 with ESC made of PWG wire (finger-disk test scheme) under conditions of friction without lubrication is 2.5 times higher than that of PW, and the wear of the “disk”

Table 2. Weight content of chemical elements, wt. %

Chemical elements	Powder wire	
	PW	PWG
Fe	37.71–71.66	13.90–27.14
Cr	12.28–30.72	4.70–26.27
B	6.64–6.70	4.60–4.62
C	5.68–22.64	40.21–70.75
O	12.08–15.69	3.83–8.02
Al	0.28–18.62	0.77–5.08
Mn	0.32–1.24	0.34–0.68
Ti	0.15–1.68	–
Si	0.57	0.50–0.75
K	0.13	–
Zn	0.27	0.48–0.90
Mg	–	0.11–0.32
Ca	–	0.54–0.77
Cu	–	0.48–0.59

(counterbody) is 28% less [25]. The coefficient of friction of the ESC from PWG is lower by 10% compared to PW.

It is worth noting the study of wear resistance of a pair from steel 45 disk after hardening and low tempering – a block with applied ESC [26], formed as an reverse friction pair with a coefficient of mutual overlap in triboconjugation 0.125 (that is, the counterbody was in contact with the disk 8 times longer), under conditions of boundary lubrication with industrial oil I-20. The results obtained showed a significant decrease in the wear of ESC from PWG with the addition of graphite (0.001 g) in comparison with ESC applied by the T15K6 alloy with the addition of graphite (0.09 g) at P = 5 MPa, v = 0.67 m/s and τ = 4 hours. In this case, the reverse pair, according to the given test mode, operated as a direct triboconjugation.

Noteworthy is the model experiment of a continuous drilling process of specimens measuring 112×32×11 mm made of steel 40X hardened to a hardness of HRC 38–40. As a tool, HSS drills were used (analog of P6M5) with a diameter of 8 mm with a cutting-point angle of 118°, the IRWIN company (Switzerland). It was found [27] that the durability of the cutting edge of a drill with ESC reinforced by PWG compared to the serial unreinforced increased almost 7 times (the number of continuous drilled holes with a depth of 11 mm was 27 vs. 4), and the durability of the reinforced cutting edge T15K6 with the addition of graphite compared to the unreinforced was only more than 3 times (14 holes vs. 4).

The effectiveness of the ESA technology using the PWG electrode is also evidenced by the

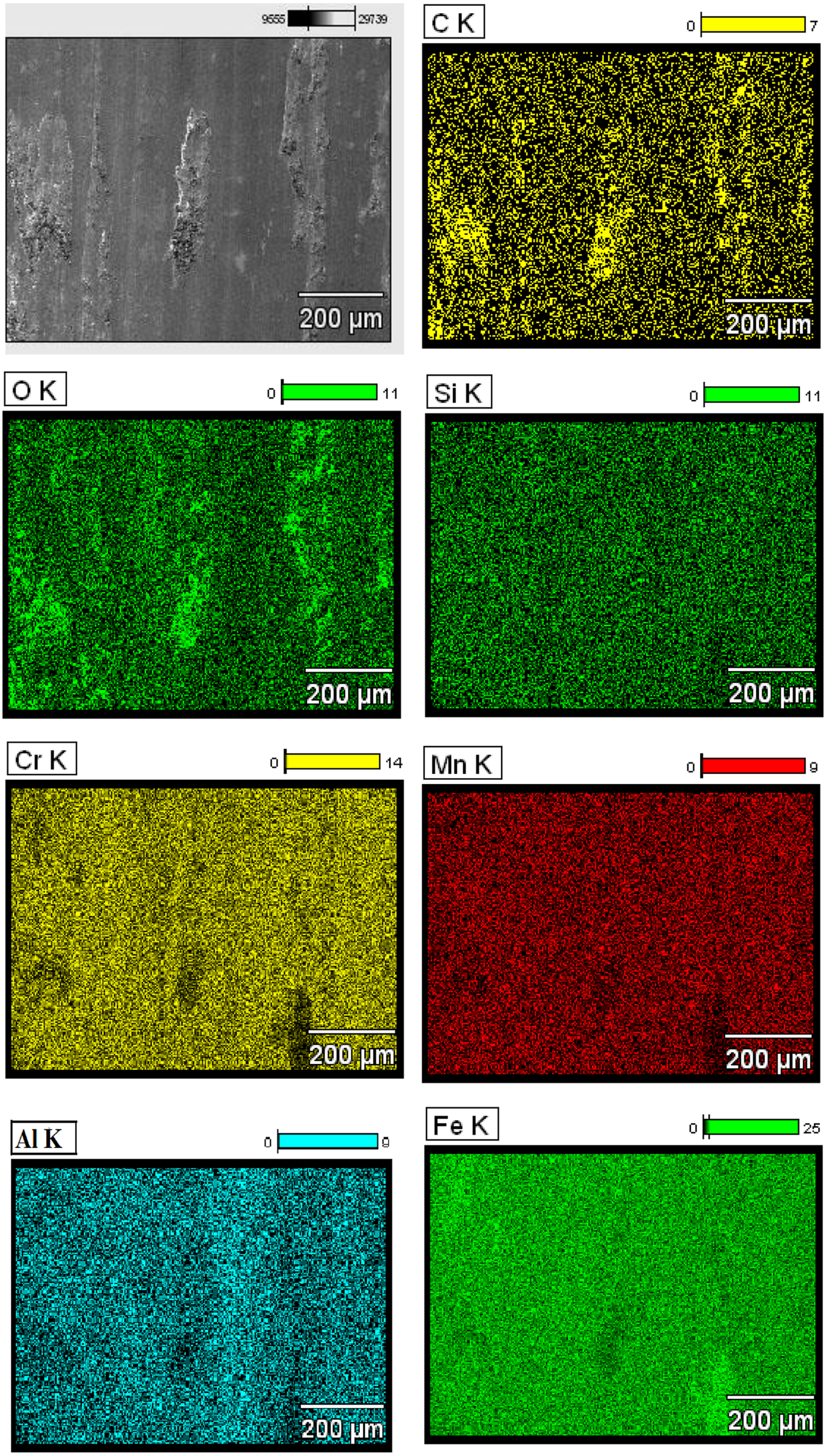

Fig. 3. Cartography of the distribution of chemical elements in the ESC from PWG

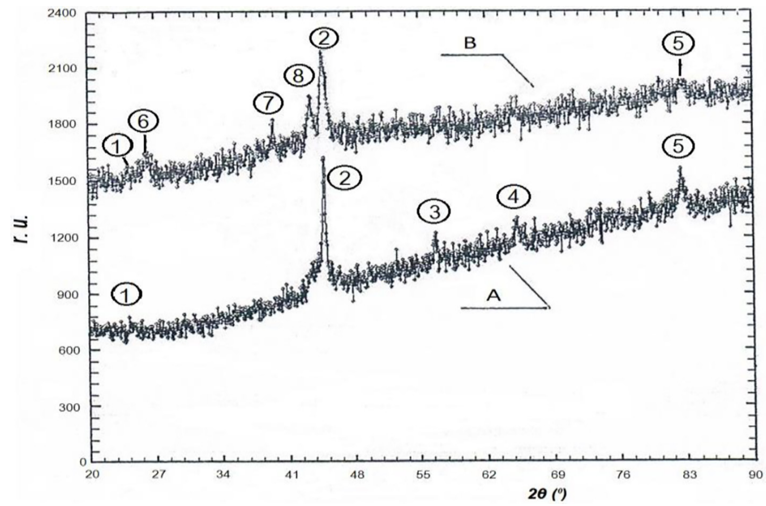

Fig. 4. Diffractograms of electric-spark coatings from PW (A) and PWG (B): 1 – (Fe,Cr) B; 2 – Fe (110); 3 – Fe_2B; 4 – Fe (200); 5 – Fe (211); 6 – B (122); 7 – $Cr_{1.65}Fe_{0.35}B_{0.96}$ (511); 8 – $Cr_{1.65}Fe_{0.35}B_{0.96}$ (131)

results of the experimental-industrial test of the reinforced teeth of a band saw made at the Teckhnolis PE (Lviv) from steel D6A (analogue of 50XGFMA), in comparison with non-reinforced teeth. Sawing of ash-wood logs (semi-frozen, with the surface covered with mud and sand, with partial presence of stones) on the VSG-1000 sawmill showed that the service life of the band saw with ESA teeth reinforced with PWG was 39 cuts against 19 cuts with non-reinforced teeth [27].

Thus, the above research data indicate the proper frictional stability of the ESC and the feasibility of using ESA technology with PW and PWG electrodes for a wide range of tasks.

CONCLUSIONS

The structure of the ESC from powder wires PW and PWG is an austenitic matrix with boride inclusions (Fe,Cr)B, iron boride Fe_2B, as well as chromium borides of iron $Cr_{1.65}Fe_{0.35}B_{0.96.}$ The absolute values of the characteristics of the micro- and submicrovolumes of the surface layer of ESC vary depending on the alloying of the electrode with PW or PWG. The distribution of the chemical elements Cr, Fe and C in the ESC from powder wires of the Fe-Cr-B-C system is uneven and varies in a fairly wide range (except for B). Frictional stability of ESC from powder wires under conditions of friction without lubrication and at boundary friction indicates the expediency of using ESA technology with PW and PWG to increase the service life of both machine parts and cutting tools.

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