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The Structure and Properties of Sprayed and Deposited Layers Obtained Using Powders Containing Ceramic Particles

Abstract: Powdered filler materials are increasingly commonly used in surfacing and spraying processes involving the use of concentrated energy (e.g. plasma arc or the laser beam). The article presents industrial applications of processes tasked with the protection of surfaces against abrasive and cavitation wear. Some of the methods enabling the obtainment of protective layers include plasma powder transferred arc surfacing or gas-powder spraying. Technological tests revealed the usability of both these technologies in relation to duplex steels and led to the obtainment of higher protection against and resistance to abrasive and cavitation wear when using NiBSi powders than those obtained by elements made of steel alone. Tests concerning resistance to abrasive and cavitation wear followed a six-month long period of operation. Test specimens were subjected to visual tests, macroscopic metallographic tests, microscopic measurements of sprayed layers and the analysis of the coating microstructure. The tests revealed the obtainment of high protective properties of coatings made using gas-powder spraying involving the post-spray remelting process.

Keywords: metal surfacing, protection of surfaces, powdered filler materials, resistance to abrasive and cavitation wear

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Introduction

The 21st century sees the revolutionary development of engineering metallic and cerametallic materials, based primarily on nickel, iron, cobalt and titanium. The aforesaid materials must satisfy high requirements, particularly connected with special tool operating conditions. In most cases, the development of new technologies and materials consists in the improvement of already existing structural materials. The development of new materials requires a special and unconventional approach in terms of manufacturing and subsequent processing.

The article discusses industrial applications of processes aimed at protecting surfaces against wear. Methods used to provide the aforesaid protection include plasma powder surfacing and gas-powder spraying performed using nickel-based powders.

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Powder composites for spraying and surfacing

Powder filler materials are increasingly often used in surfacing technologies involving the use of concentrated energy beams, i.e. plasma and laser surfacing, as well as in spraying processes. The use of powder filler materials enables the obtainment of overlay welds characterised by varied chemical and phase compositions, which, in turn, leads to the obtainment of coatings characterised by high functional properties. The primary composite materials used to improve tribological properties of machinery and equipment are nickel, cobalt and iron-based materials. The reinforcing task is usually "delegated" to high-melting phases, e.g. transition carbides of groups IVB-VIB of the periodic table of elements [1]. Table 1 presents primary groups of engineering materials used to protect elements against various types of wear.

In accordance with the above-presented table as well as numerous scientific publications and research works, nickel-based alloys are the most popular materials used to protect elements against various types of wear. Numerous tests have demonstrated that the welding method-based deposition of coatings enables even a several-fold increase in the service life of elements (by modifying their surface properties) [3]. The most frequently used materials are NiCrBSi powders, whose alloys are characterised by a hardness of up to 65 HRC. The primary component of the aforesaid alloys, providing their plasticity and high corrosion resistance, is nickel. Chromium significantly increases both corrosion and wear resistance. Boron and silicon are responsible for a decrease in the melting point of alloys and are characterised by fluxing effect. Boron is also a component responsible for higher abrasive wear resistance (by forming boride phases or carboborides). During the cooling of NiCrBSi alloys, nickel crystallises first (with eutectics to follow). The hardness of the nickel alloy is restricted within the range of 300 HV to 400 HV, whereas that of the Ni-Ni3B eutectics amounts to approximately 450 HV. The hardness of carboborides eutectics is restricted within the range of approximately 600 HV to 650 HV. However, certain reference publications inform about eutectics, the hardness of which exceeds 800 HV. Abrasive wear resistance tests justified the use of nickel alloys on surfaces of mining equipment elements, e.g. excavator scoops, coal-cutting machine elements, worms for transporting bulk materials, etc. [4].

By being highly resistant to abrasive wear, hard phases significantly improve functional properties of overlay welds. One of the key

Table 1. Groups of materials and corresponding types of wear prevented by them [2]

Type of wear	Sprayed materials
Atmospheric corrosion	Wires with Zn, alloys: Zn-Al, Al, Al-Mg Powders: Al_2O_3, Al_2O_3-TiO_2, CrO_2
	All of the above-named materials + stainless steels and NiCr-based alloys
High-temperature corrosion	Wires: Al, alloys with a high content of chromium in the nickel or iron matrix Powders: ZrO_2, ZrO_2+Y_2O_2 and others
	Powders: ZrO_2, ZrO_2+Y_2O_2 and other materials characterised by high thermal properties
	Al, alloys with a high content of Cr in the nickel or iron matrix
Abrasive wear	Self-fluxing type powder (inclusive of melting)
	Iron or nickel-based wires modified by carbide, boride or silicide phases
	Composite powders: WC-Co, WC-Co-Cr, NiCr-CrC, WC and CrC-Ni
Abrasive-corrosive wear at high temperature	Nickel-based wires modified by carbide, boride or silicide phases
	NiCr-Cr_2C_2 type powders with modifying agents, e.g. Cr_2C_2-NiCr or WC-Cr

factors concerned with the joining of the hard phase with the matrix is the wettability of the hard phase in the matrix material. Another important factor connected with the making of composite overlay welds is the difference between the density of the hardening phase and that of the matrix. Attention should also be paid to the tendency where heavier particles settle in the lower area of the overlay weld, whereas the lighter and less resistant phases accumulate in the upper zone of the overlay weld. The aforesaid tendency adversely affects properties of coatings as it is the hardening phase (i.e. carbides or nitrides) that is responsible for preventing the friction-triggered degradation of elements [1].

Industrial application of nickel alloy-based coatings

Gas-powder spraying of elements made of duplex steel

Research problem

The observation of elements made of duplex steel X2CrNiMoN25-7-4, constituting heating elements of a furnace system, revealed gradual damage to protective cover plates through erosion and wear triggered by dust affecting the support elements of the aforesaid system. The above-presented issue necessitated the protection of cover plate surfaces in order to prolong the service life of the device. The thickness of the cover plates amounted to 3 mm. Because of fixing-related restrictions, the thickness of the protective coating should be ≤ 0.5 mm. Figure 1 presents the protective cover plate surface after operation.

Fig. 1. Surface of 290 mm long cover plates after operation

The selection a technology and metallic powders for the spraying of an abrasion-resistant coating

Because of the restrictions concerning the thickness of the protective layer and the small thickness of the elements, the two processes selected to provide surface protection were the following:

- **spraying with simultaneous melting (Eutalloy process)** – consisting in covering the element surface (previously appropriately prepared and heated to a temperature restricted within the range of 200 °C to 800°C) with a powder coating. The process involves the melting of the powder coating and the partial melting of the base material. The joint between the coating and the base material is primarily of diffusive and, to a slight extent, metallic nature. The coating is characterised by very good adhesion to the element surface as well as by smoothness and density, which, depending on the chemical composition of the coating material, enables the exposure of elements to abrasive and corrosive factors as well as dynamic loads. The recommended coating thickness is restricted within the range of 0.15 mm to 2.0 mm [2],
- **spraying with subsequent melting (Eutalloy RW process)** – consisting in the spraying of powder on the element surface (previously appropriately prepared and heated to a temperature restricted within the range of 100°C to 300°C), using a torch located between 150 mm and 200 mm from the surface, followed by melting performed using a multi-flame torch of high thermal power. The coating is joined with the base material primarily through diffusion resulting from the spraying and the melting of the coating, without the partial melting of the base material. The layer obtained in the above-presented manner

is characterised by good adhesion to the substrate, the lack of porosity and high smoothness. Elements provided with the sprayed coating can be exposed to abrasive wear, corrosive factors, high temperature and moderate dynamic loads. The recommended coating thickness is restricted within the range of 0.5 mm to 2.0 mm.

The selection of the spraying processes entailed the selection of powders used in technological tests. The selection of the powders was based on requirements concerning coatings exposed to expected operating conditions. The selected powders included those based on the Ni-Cr-B-Si-Fe alloy containing tungsten carbides (TungTec 10112 and Eutalloy RW 12112) and powders not containing tungsten carbides (BoroTec 10009 and Eutalloy RW 12496) [3]. The chemical composition of the powders is presented in Table 2 (in accordance with the manufacture's inspection certificate 3.1 (Castolin Eutectic Ireland Ltd.)).

After melting, the coatings deposited using the flame spraying process and a SuperJet **Eutalloy** torch contained traces revealing burnouts of alloying components (dark areas in Fig. 2). The aforesaid phenomenon could probably result in the decreased wear resistance of the coatings. The tests were performed using a Q4 Tasman spark emission spectrometer (Bruker). The results of analysis are presented in Table 3.

Fig. 2. Burnouts of the alloying components of the coating sprayed using the BoroTec 10009 powder; marked areas selected for chemical composition analysis
(b – superheated area)

The chemical composition analysis revealed that the coating in the superheated area was characterised by a decreased content of (burnt-out) nickel, which was by approximately 12% lower than the appropriate value. The content of boron was reduced by 0.37%, the content of silicon was reduced by 1.49%, whereas the content of carbon was reduced by 0.28%. In addition, the superheated area was characterised by a significant increase in the content of iron, in comparison with the inspection certificate and the proper value (observed in area a in Figure 2). The foregoing phenomenon indicated

Table 2. Chemical composition of the test powders in accordance with inspection certificates [% by weight]

Powder name	B, %	C, %	Cr, %	Fe, %	Si, %	Ni, %	WC, %	Hardness
Borotec 10009	3.33	0.78	15.26	4.22	4.22	bal.	-	59 HRC
Tungtec 10112	3.09	0.06	6.89	6.09	4.39	bal.	60	64 HRC
Eutalloy RW 12112	3.3	0.83	15.77	4.11	4.27	bal.	35	720 HV_{30}
Eutalloy RW 12496	3.36	0.81	16.6	4.03	4.33	bal.	-	730 HV_{30}

Table 3. Chemical composition of the BoroTec 10009-based coating in areas a in b in Figure 2

Contents of chemical elements, % by weight	Area subjected to tests in accordance with Figure 2		Content of chemical elements according to the inspection certificate, %
	area a	area b	
B	2.63	2.26	3.33
Fe	4.26	17.80	4.22
Si	4.42	2.91	4.22
C	0.85	0.57	0.78
Cr	17.49	16.97	15.26
Ni	70.08	58.04	72.19

the diffusion of iron from the base material to the coating.

The problems connected with spraying, resulting from the small thickness of the cover plates and, consequently, the high susceptibility of the sprayed coating to superheating and significant post-spray deformation necessitated the replacement of the previously applied thermal spray technology with the **Eutalloy RW** process. The coatings were sprayed using a CastoDyn DS 8000 torch (Castolin) (Fig. 3).

Filler materials used in the deposition process were Eutalloy RW 12112 and Eutalloy RW 12496 powders. The detailed technological conditions of spraying process are presented in Table 4.

The technological spraying tests involving the cover plates revealed the effect of surface processing on the formation and adhesion of the coating. After abrasive treatment performed using an abrasive disk, during the melting process, the coating tended to drip and curl (Fig. 4 a). In turn, the coating was formed properly if the substrate had been subjected to abrasive blasting with electrocorundum (Fig. 4 b).

Fig. 3. CastoDyn DS 80000 torch

Table 4. Technological conditions of the Eutalloy RW process used in the spraying of the test cover plates

No.	Activity	Technological remarks	Gas pressure
1	Wiping the entire elements with lint-free cloth saturated with isopropanol	acetone being also applicable	
2	Dry heating up to 100°C	oxy-acetylene torch, the GR3 cap	
3	Surface preparation – abrasive blasting with electrocorundum	F22 fraction electrocorundum	
4	Fixing the plate in the device or fixing the covers on the plate	cover plate placed horizontally; steel cover protected by Solution R104 paste	
5	Surface temperature control with a contact thermometer	in the case of temperature <50°C - preheating of the surface up to 80°C using the CastoDyn DS 8000 torch	
6	Deposition of powder 10112 using the CastoDyn DS 8000 torch (module SSM 20); layer thickness: 0.7 mm	spraying distance: 200 mm – spraying direction: longitudinal in relation to the element; change of the spraying direction outside the element surface; obtainment of the coating thickness after a minimum of 4 runs of the torch	Oxygen pressure: 4 bars, acetylene pressure: 0.7 bar
7	Removal of the plate from the device or the removal of the steel covers from the plate	plate longitudinal axis positioned at an angle of 30°	
8	Melting of the coating	oxy-acetylene torch with a multi-flame nozzle, the 12-hole GR5 cap; melting process initiated at the bottom, continued upwards and performed with a weaving move	Oxygen pressure: 4 bars, acetylene pressure: 0.7 bar
9	Cooling of the plates under an insulating mat		

Figure 5 presents the spraying of the cover plates followed by the melting of the coating using the CastoDyn DS 8000 torch 5.

The technological spraying tests with subsequent melting performed using the CastoDyn DS 8000 torch revealed that the use of the Eutalloy RW 12112 and Eutalloy RW 12496 powders contributed to the stable course of the process and the significantly lower porosity of the coatings than that of the coatings obtained through spraying performed using the SuperJet Eutalloy torch as well as the Borotec 10009 and Tungtec 10112 powders. The coatings after the spraying process are presented in Figure 6.

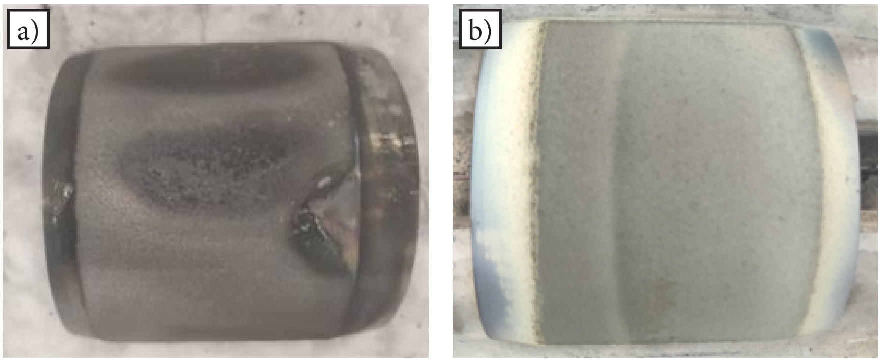

Fig. 4. Elements after spraying in relation to the surface preparation method involving: a) grinding and b) abrasive blasting

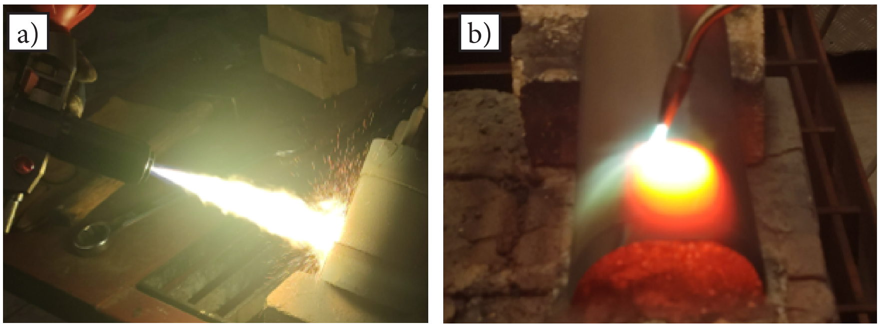

Fig. 5. Processes: a) spraying and b) melting

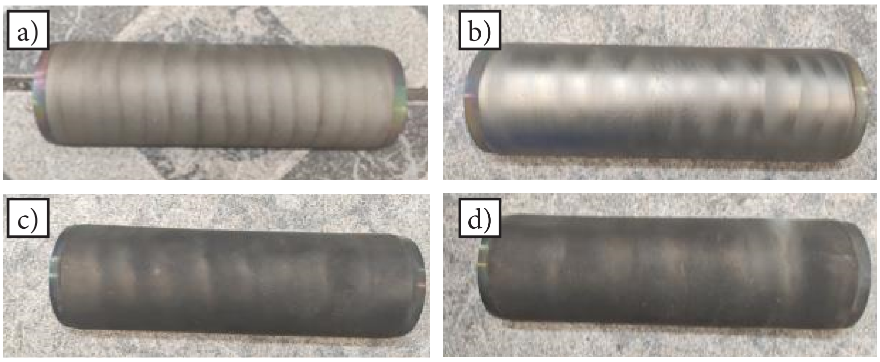

Fig. 6. Coatings sprayed using: a) Eutalloy RW 12112, b) Eutalloy RW 12496, c) Borotec 10009 and d) Tungtec 10112 powders

Laboratory tests of sprayed coatings

Laboratory tests of thermally sprayed coatings included observation by the unaided eye, aimed to determine whether the coatings contained, if any, the following welding imperfections:

- surface irregularity,
- surface-breaking cracks,
- pellets,
- roughness differences.

The visual assessment of coatings quality did not reveal the presence of the above-named imperfections. The visual tests were followed by macroscopic metallographic tests. The observation results are presented in Figure 7.

The macroscopic tests of the coatings revealed significant differences in the quality of the coatings deposited on the plates and obtained using the powder spraying process with simultaneous melting (Eutalloy process) and subsequent melting (Eutalloy RW process). The coatings obtained using subsequent melting and the Eutalloy RW 12112 and Eutalloy RW 12496 powders were characterised by significantly lower porosity than those obtained using simultaneous melting and the BoroTec 10009 and TungTec 10112 powders. In the coating sprayed with the TungTec 10112 powder it was possible to observe the lacking continuity of the coating on the adhesion line, where the coating itself was characterised by the highest roughness and surface irregularity (confirmed by the macroscopic tests (Fig. 8 b)).

The macroscopic metallographic tests were followed by microscopic tests performed in accordance with the guidelines specified in the PN-EN ISO 1463:2006 standard [6]. The results

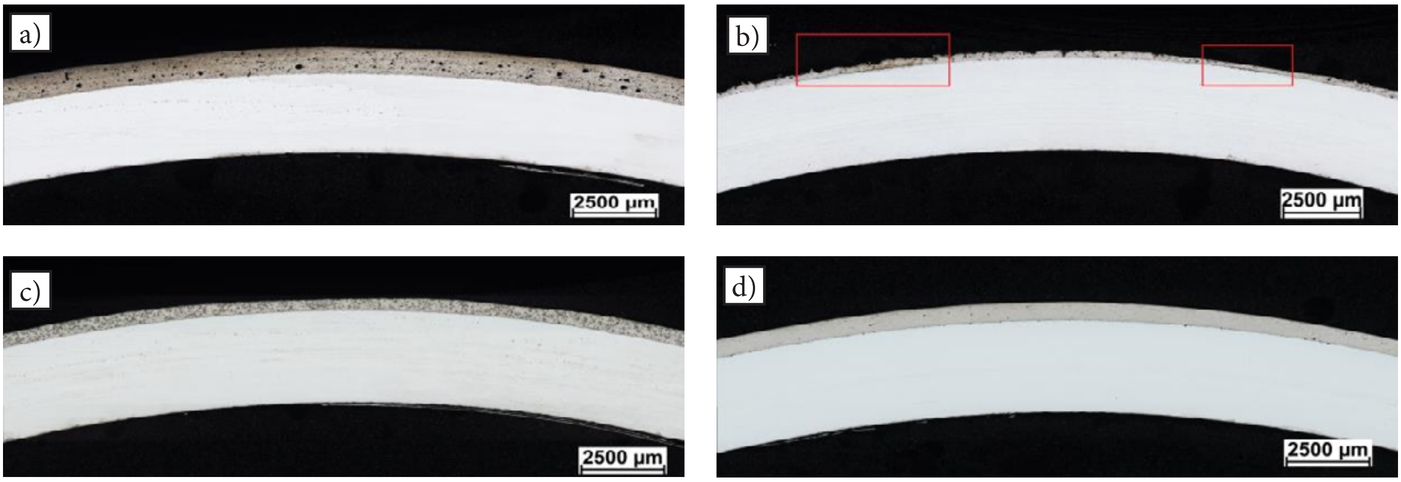

Fig. 7. Macrostructure of the coatings sprayed with the following powders: a) Borotec 10009, b) TungTec 10112, c) Eutalloy RW 12112 and d) Eutalloy RW 12496

of the microscopic observations are presented in Figure 8.

Microscopic measurements concerning thicknesses of the coatings revealed that the smallest thickness was that of the coating sprayed using the TungTec 10112 powder; the average thickness amounting to 234.4 µm. In turn, the greatest thickness was obtained using the Borotec 10009 powder; the average thickness amounting to 990.2 µm. During the melting process, the thinner coating was superheated, which led to the delamination of the coating from the base material. As a result, it was necessary to perform another run of the spraying process and increase the coating thickness. The average thickness of the coating

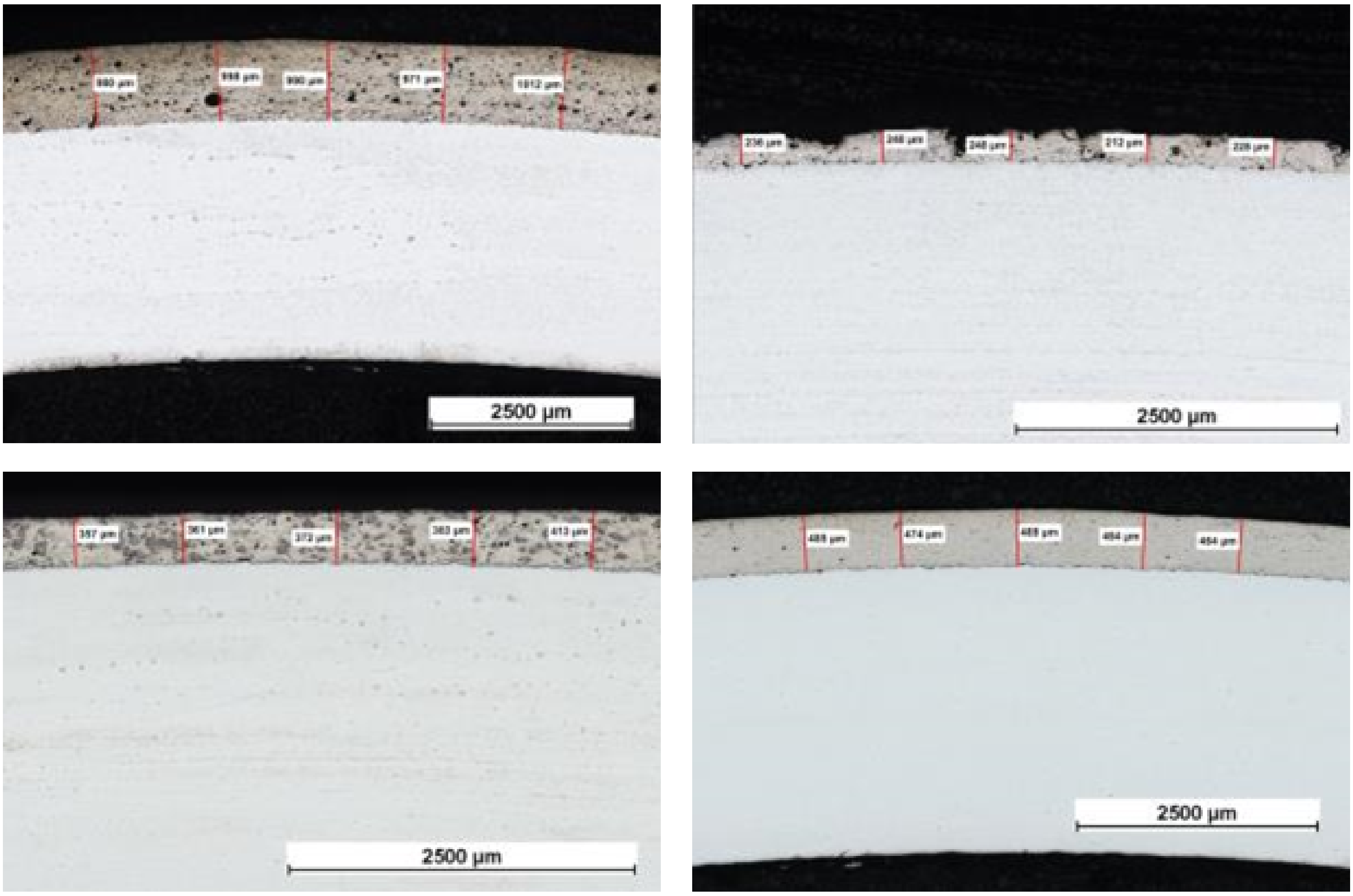

Fig. 8. Thickness measurement results in relation to the coatings sprayed with the following powders: a) Borotec 10009, b) TungTec 10112, c) Eutalloy RW 12112 and d) Eutalloy RW 12496

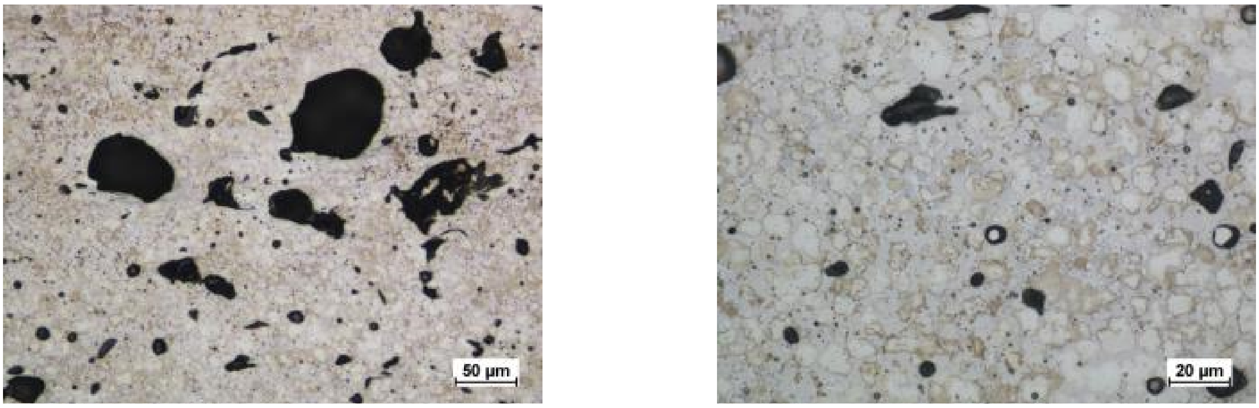

Fig. 9. Results of the microscopic tests of the sprayed coating made using the Borotec 10009 powder; magnification: a) 200x and b) 500x

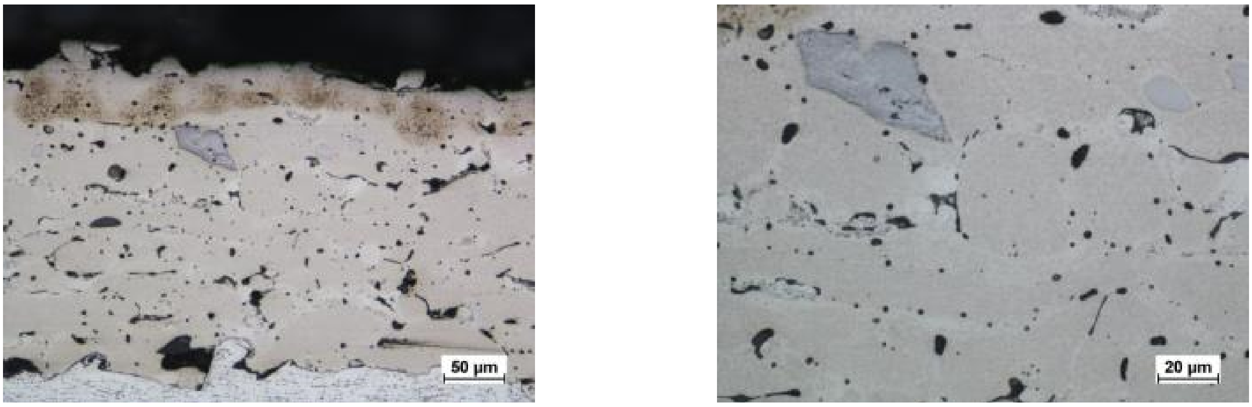

Fig. 10. Results of the microscopic tests of the coating made using the TungTec 10112 powder; magnification: a) 200x and b) 500x

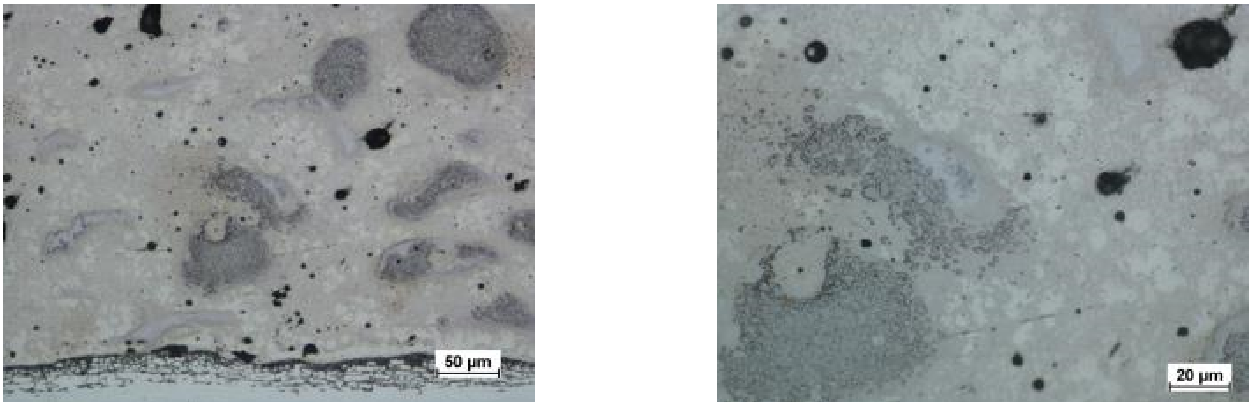

Fig. 11. Results of the microscopic tests of the coating made using the Eutalloy RW 12112 powder; magnification: a) 200x and b) 500x

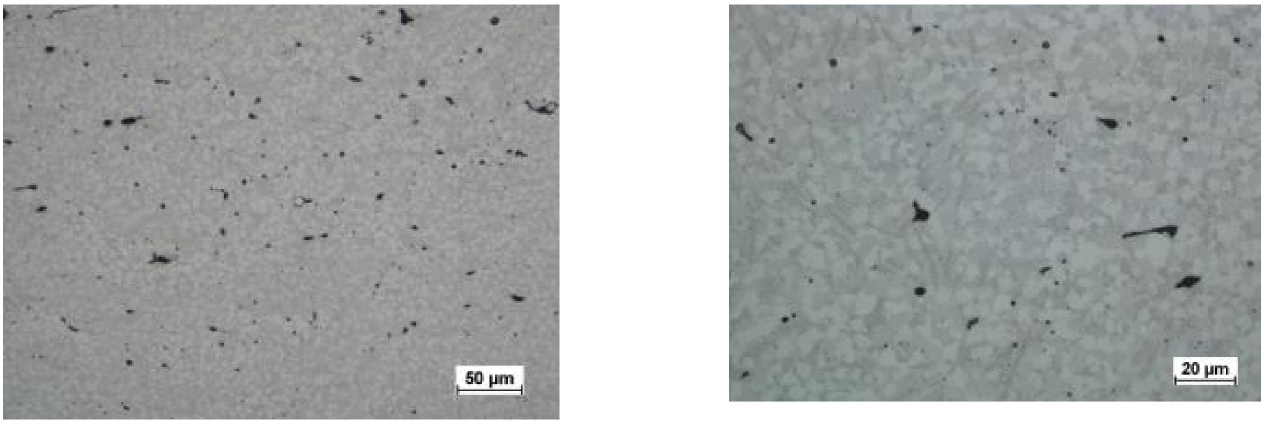

Fig. 12. Results of the microscopic tests of the coating made using the Eutalloy RW 12496 powder; magnification: a) 200x and b) 500x

Fig. 13. Changes on the surface of the coating made using the Eutalloy RW 12496 powder

Fig. 14. Changes on the surface of the coating made using the Eutalloy RW 12496 powder

sprayed using the Eutalloy RW 12112 powder amounted to 377.2 µm, whereas the thickness of the coating sprayed using the Eutalloy RW 12496 powder amounted to 479.2 µm, which confirmed that the Eutalloy RW process satisfied the requirement related to the coating thickness (≤ 0.5 mm).

The microscopic tests also involved observations of the sprayed coatings, performed using a magnification of 200 times and that of 500 times. The observation results are presented in Figures 9–12.

The microscopic metallographic tests revealed that the coatings made using the RW 12112 and Eutalloy RW 12496 powders were characterised by lower porosity than that characteristic of the coatings made using the Borotec 10009 and TungTec 10112 powders.

Operational tests of the coatings after 6 months' operation

Visual assessment of the coatings

The visual assessment concerned with the quality of the coatings revealed the presence of particles resulting from the use of the plates.

The visual tests of the elements made using the Eutalloy RW 12496 powder revealed clearly visible changes in the coating areas such as hollows or scratches, implying operation-induced abrasion (see Figures 13 and 14).

The visual tests of the elements made using the Eutalloy RW 12112 powder revealed characteristic discolouration. The discolouration probably resulted from the contact of the cover plate with the mounting seat. The coating did not contain any scratches or hollows. Figure 15 presents the coating areas affected by discolouration.

Fig. 15. Discolouration on the surface of the coating made using the Eutalloy RW 12112 powder

The visual assessment of the plates made using the Eutalloy RW 12112 powder did not reveal changes in the coatings resulting from the operation of the elements.

Measurements of coating thicknesses after operation

Measurements of the sprayed layers were performed using the microscopic method (in accordance with the guidelines contained in the PN-EN ISO 1463:2021) [5]. The areas subjected to the tests were selected so that measurement

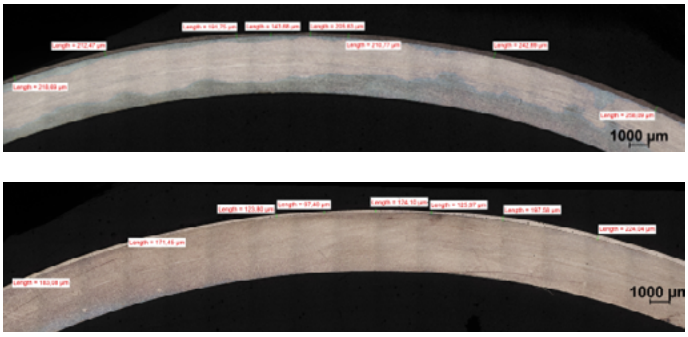

Fig. 16. Results of measurements concerning the thickness of the sprayed layer after operation

could involve the plate areas characterised by the most intense wear. In cases of the plates which did not contain traces of operation-induced wear, the test area was located centrally in the plate axis. The measurement results are presented in Figures 16a–b and 17a–d.

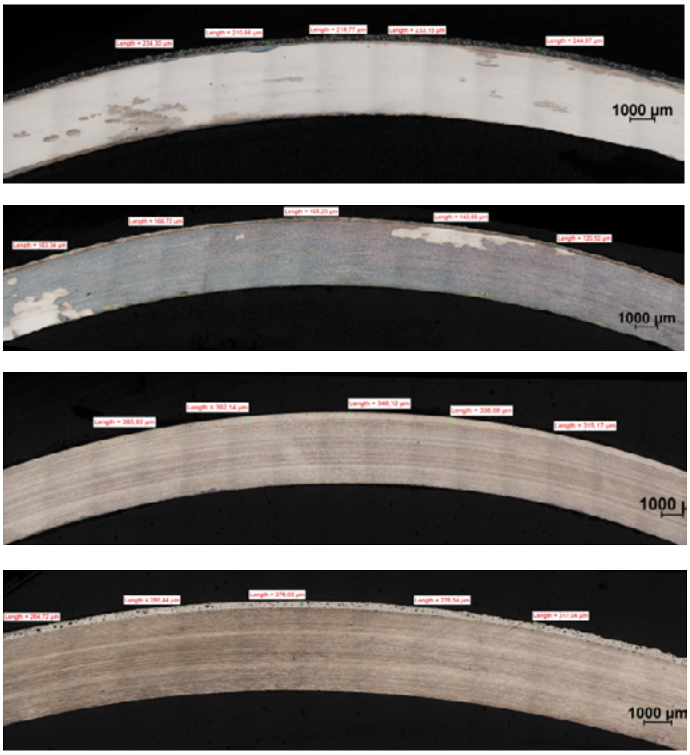

Fig. 17. Results of measurements concerning the thickness of the sprayed layer after operation

The microscopic measurements concerning coat thickness revealed than none of the coatings underwent entire operation-triggered wear. Depending on the cover plate, the thickness of the coatings was restricted within the range of 97.40 µm (coating sprayed using the Eutalloy RW 12496 powder) to 395.30 µm (coating sprayed using the powder containing tungsten carbide). The visual tests revealed that the greatest damage (changes of the sprayed coating thickness) was observed in the coating made using the Eutalloy 12496 powder. The criterion adopted in the analysis was not the coating thickness itself (as the tests revealed that each coating was characterised by different thickness) but thickness amplitude (indicating the wear of the layer in the area characterised by the smallest thickness). The above-presented approach revealed that the highest percentage amplitude was observed in the coatings made using the Eutalloy 12496 powder (thus indicating their lowest wear resistance). Figure 18 presents the microstructure of the coating made using the Eutalloy RW 12496 powder, in the area affected by abrasive wear. For comparative purposes, Figure 19 presents the microstructure of the coating made using the Eutalloy 12112 powder.

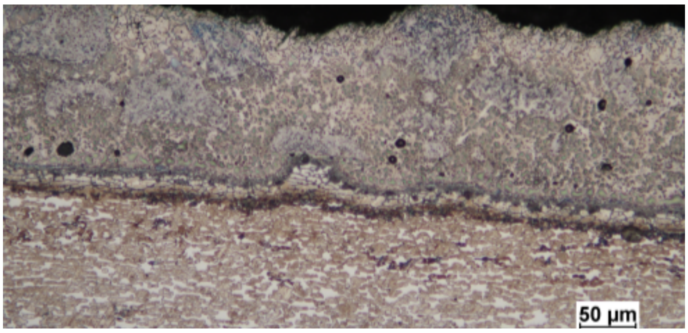

Fig. 18. Microstructure of the coating on cover plate 6c 1 (mag. 200x), in the area affected by wear – characteristic operation-triggered changes of the surface

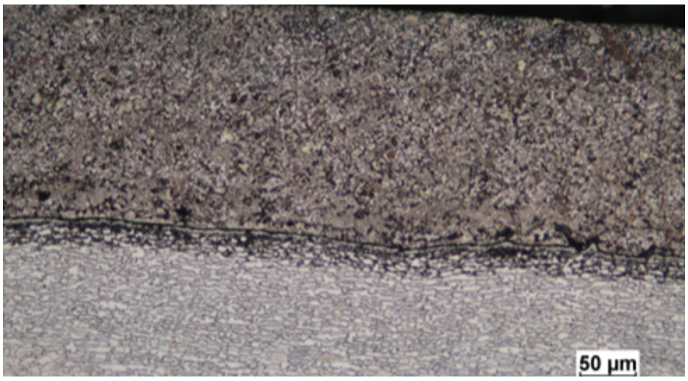

Fig. 19. Microstructure of the coating (on the cover plate) made using the powder containing tungsten carbides (Eutalloy RW 12112) (mag. 200 x); the lack of operation-triggered wear traces

Summary of tests

The above-presented tests involved the analysis of many variables affecting the stability of the spraying process and the quality of the coatings. The tests involved the use of four powder grades (TungTec 10112, Borotec 10009, Eutalloy RW 12496 and Eutalloy RW 12112) and two variants of the flame spraying technology:

- with simultaneous melting (performed using the SuperJet-S Eutalloy torch),
- with subsequent melting (performed using the CastoDyn DS 8000 torch and the multi-flame torch (used to melt the coating).

Table 5. Chemical composition of the powders used in the plasma powder surfacing process

Content of chemical elements*	C [% by weight]	Si [% by weight]	B [% by weight]	Ni [% by weight]	Fe [% by weight]
Höganäs 1559-40	<0.06	3.0	2.9	bal.	0.2
DURMAT 61-PTA (40% DURMAT 59-PTA 60% DURMAT FTC)*	<0.1	3	3	bal.	<2
*Powder contains 60% (by weight) of WC					

The tests revealed that significantly better results were obtained using the Castodyn DS 8000 torch and the Eutalloy RW 12496 and Eutalloy RW 12112 powders (Castolin). The visual tests revealed the lack of imperfections on the surface of the coatings made using the above-presented technology.

The macro and microscopic metallographic test results revealed that the highest quality (manifested by the lowest roughness) was that of the coatings sprayed using the Eutalloy RW 12496 and Eutalloy RW 12112 powders. The microscopic thickness measurements revealed that the coatings made using the Eutalloy RW 12496 and Eutalloy RW 12112 powders satisfied thickness-related requirements, stating that the coating thickness should not exceed 0.5 mm.

Exemplary plasma powder surfacing of pump elements made of duplex steel

The tests involved a stopper ring of a wpwe-100/5 pump (being an element of the pump relief system (hydraulic bearing)), used in the Eti Bakir copper mine near the city of Siirt. An aggressive work environment was responsible for the intense wear of pump elements (through abrasion and cavitation). The elements of the pump subjected to the tests were made of duplex steel. Figure 20 presents a pump element.

To improve the service life of the elements it was necessary to perform the plasma powder surfacing process using two types of powder (i.e. with and without tungsten carbides). The chemical composition of the powders used in the tests is presented in Table 5.

Fig. 20. Pump element

The surfacing process was performed using a Eutronic GAP 3001 DC machine (Castolin). The surfacing process parameters (identical in relation to both powders) are presented in Table 6. The elements after the surfacing process are presented in Figure 21 a–c.

Table 6. Surfacing process parameter

Current	82 A
Arc voltage	29.5 V
Mset	40 %
Shielding gas flow rate	15 l/min
Carrier gas flow rate	3.7 l/min
Plasma-forming gas flow rate	1.2 l/min

The fixing of the element in the pump necessitated the processing of the overlay weld (aimed at the obtainment of flat surface). In terms of the overlay weld made using powder from the NiBSi group (Höganäs 1559-40) it was possible to apply removal machining (turning or milling). However, the above-named processing required the use of tools made of sintered carbides. The overlay welds made using the powder containing tungsten carbides could only be subjected to grinding as (in the

Fig. 21. Elements after the surfacing process performed using: a) DURMAT 61-PTA powder and b) and c) Höganäs 1559-40 powder

above-named case) removal machining could damage either the tool or the element (see Figure 22).

The improper machining of the element resulted in damaging the latter. As a result, the element could not be fixed in the device, which, consequently, precluded the determination of its service life.

Figures 23 and 24 present the microstructure of the overlay weld made using the DURMAT 61-PTA powder (containing tungsten carbides).

Fig. 22. Damage caused by improper machining

Macroscopic metallographic tests revealed the presence of cracks and porosity in the overlay weld. Porosity is an undesired phenomenon treated as an imperfection. In turn, cracks present in the overlay welds used for protecting surfaces against metal-mineral friction-triggered abrasion are not treated as imperfections.

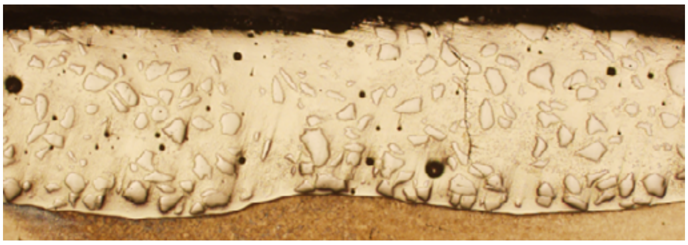

Fig. 23. Microstructure of the overlay weld made using the DURMAT 61-PTA powder

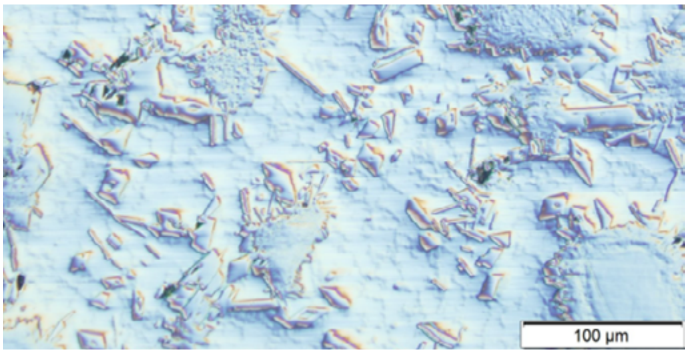

Fig. 24. Microstructure of the overlay weld containing tungsten carbides; Nomarski contrast; mag. 400x

Tests of coatings sprayed under operating conditions

Information obtained from the pump manufacturer said that the plasma surfacing process performed using the NiBSi type powder (Höganäs 1559-40) extended the service life of the device by between 5 and 9 times (depending on measurements). It could be assumed that coatings made using the powder containing tungsten carbides (DURMAT 61-PTA) could protect the element even more effectively. Regrettably, machining-triggered damage to the element precluded the verification of the above-presented hypothesis. However, tests involving the use of the DURMAT 61-PTA will be performed in the future.

Conclusions

1. The tests discussed in the article revealed the usability of both plasma powder surfacing and gas-powder spraying on duplex steels.
2. The tests revealed the successful application of NiBSi type powders in the protection of elements against abrasive and cavitation wear as well as the significant improvement of resistance of elements made of duplex steels.
3. The spraying technology involving the use of the CastoDyn DS 8000 torch and post-spray melting enabled the obtainment of coatings characterised by required quality and thickness (max. 0.5 mm).
4. The tests revealed that the coatings made using the powder containing tungsten carbides provided significantly better protection against abrasive wear than the coatings made using the NiCrBSi type powder (not containing tungsten carbides).

References

[1] Bober M.: Otrzymywanie i struktura kompozytowych warstw Ni-NbC napawanych plazmowo. Przegląd Spawalnictwa, 2018, vol. 90, no. 5.

[2] Dobrzański L.A., Dobrzańska-Danikiewicz A.D.: Kształtowanie struktury i własności powierzchni materiałów inżynierskich, Wydawnictwo Politechniki Śląskiej, Gliwice 2013.

[3] Pekalski G., Mucha T., Lipińska A.: Problemy materiałowe i remontowe czerpaków koparek węgla brunatnego, Górnictwo Odkrywkowe vol. R. 52, no. 3-4, 2011

[4] Nastaj T.: Badanie odporności na zużycie ścierne powłok napawanych stopami na bazie niklu, Eksploatacja i niezawodność, 2003, no. 2.

[5] PN-EN ISO 1463:2021 „Powłoki metalowe i tlenkowe – Pomiar grubości powłoki – Metoda mikroskopowa”