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IMPROVING THE RELIABILITY OF POWER COMPLEX EQUIPMENT BY ELECTRIC ARC SPRAYING

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ABSTRACT

The aim of the work is studying the efficiency of spraying application to improve the reliability of TPPs power equipment. A feasibility study indicated that the introduction of spraying technology can reduce losses in case of TPPs emergency shutdowns by 1.5–3.0 times a year, and the estimated extension of the service life of surfaces increases by 1.7–2.5 times. Since the main type of wear in the feed-water economizer (FWE) of TPP boilers is ash wear, and corrosion between the spacing bars, a comprehensive solution was proposed for the problem of extending the service life of boiler waterwall tubes and economiser tubes through development of new heat-resistant and wear-resistant thermal coatings.

KEY WORDS: spraying, welding, thermal power plant, ash wear, corrosion, electric arc coating

A significant number of failures in the operation of thermal power plant (TPP) equipment is predetermined by damages in boiler equipment, especially heating surfaces. Factors that lead to their malfunction can be divided into operational and nonoperational damages. The first group includes ash wear (typical for feed-water economizer (FWE) tubes), electrochemical and high-temperature corrosion (tubes of radiation and convective part of the boiler), metal overheating, etc. Nonoperational damages to TPP heating surfaces are most often caused by metallurgical and technological defects in the metal of tubes, low-quality manufacture, etc. [1]. Experience shows, that damages not in all heating surfaces of the boiler lead to a sudden shutdown of the power unit. In this regard, damages to FWE tubes in all cases cause failure of equipment. The main cause for such failures is ash wear. According to [2, 3], at individual power units, a number of failures caused by ash wear of boiler tubes, reaches 60 %. The mechanism of erosion wear of FWE tubes, which, according to the generally accepted theory, is caused by the effect of volatile ash particles, having high hardness and abrasiveness, is well studied [4, 5]. However, choosing an effective method of protection against wear is still a difficult task. Since the main type of wear of tube elements of TPP power equipment is ash wear and corrosion, in order to improve their reliability, service life and effi-

Figure 1. Electric arc spraying

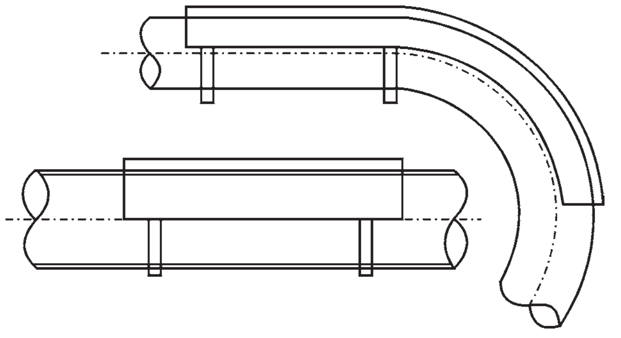

Figure 2. Individual sealing rings for protection of bends and straight sections of tubes

ciency, it was proposed to use electric arc spraying as a method of thermal modification of heating surfaces (Figure 1).

The most vulnerable areas of FWE are the first and second return bends downstream with the gas flow in opening to the section until the first spacing bars, inner and outer return bends, extreme coils from the back side of the convection shaft over the whole width. Traditionally, for individual protection of coils, sealing rings of a segment shape are used (Figure 2) [6], which are mounted on the front part of tubes downstream with the gas flow. Butt plates (Figure 3) are mounted also in other areas prone to intense ash wear.

In connection with a significant wear of technological equipment, the issue of its effective repair is now very acute, which provides the restoration of serviceability, increase in reliability, extension in the service life while reducing the costs on repair and restoration works [7]. One of the ways to improve the reliability of power plant equipment [8, 9] is its protection against ash and corrosion wear by spraying. An intensive wear of heat exchange surfaces of TPP boilers, in particular, waterwall tubes and economizer tubes, is predetermined by the use of coal dust with most of the solid noncombustible impurities as a fuel [10–12]. According to classification criteria, analysis of damages [13] shows that the main cause of damage to boiler tubes is corrosion and erosion wear. According to [14], in some units its share reached 60 %. Especially often erosion affects FWE coils. Abrasive ash particles, which are captured by flue gases at a high speed, hit the surface of the tubes and cause ash wear (Figure 4).

On the surface of waterwall tubes of 12Kh1MF steel, at temperatures elevated to 585 °C, films of iron oxides are formed, which have a weak adhesion to the steel surface and are easily worn by abrasive particles. Wear of the outer surface of tubes occurs uniformly over a large area and is localized in certain places. When the critical thickness of the tube wall is reached, it bursts, which leads to the shutdown of the power unit. The heat load on the outer wall

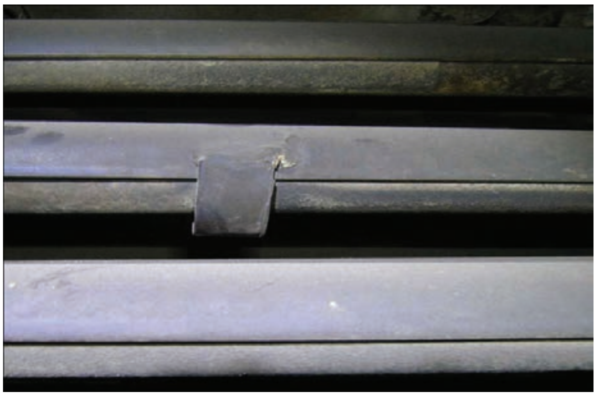

Figure 3. FWE tubes with butt plates of ash wear protection

of the tube is also increased because of the deposition of salts on the inner surfaces of waterwall tubes, which, in addition, experience corrosion and erosion damages. Therefore, the development of new effective methods to improve the reliability of TPP power equipment is an urgent direction. Damages of tube elements of heating surfaces of TPP power equipment have a nature of creep mechanisms with manifestation of fatigue, erosion and gas corrosion (oxidation) because of extremely high operating conditions, associated with high temperatures, cyclic loads and aggressive working environment, as well as because of abrasive action of coal fuel combustion products [11, 12]. Since the main type of wear on the water economizer of TPP boilers is ash wear and between the spacing bars corrosion exists, the works [12, 15] proposed a comprehensive solution to the problem of extending the service life of waterwall tubes of boilers and economizer tubes by developing new heat-resistant and wear-resistant thermal coatings [16, 17]. As a result, in the structure of such coatings, during the operation of boiler tubes and economizer tubes, dispersion hardening processes will take place as a result of precipitation of fine phases of carbides, nitrides and intermetallics, which will significantly increase their service properties during operation [18]. The aim of the article is to study the use of electric arc spraying, performed by LLC «REZON» (metallization) to improve the reliability of power equipment of TPP.

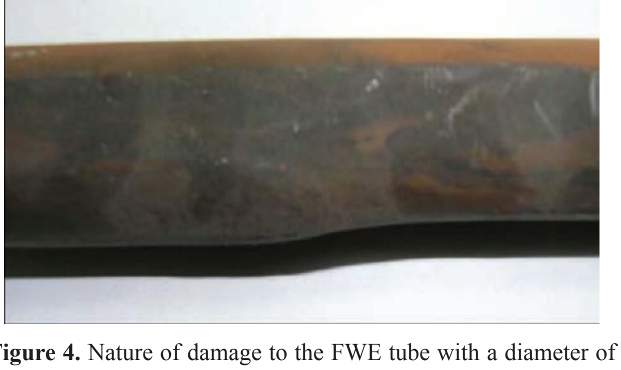

Figure 4. Nature of damage to the FWE tube with a diameter of 32×6 mm as a result of action of ash wear

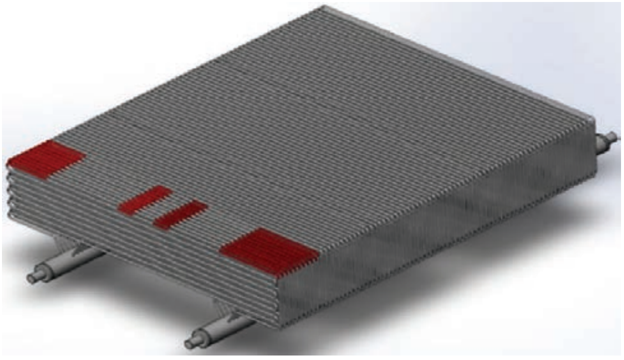

Figure 5. Areas of intensive ash wear of FWE tubes: straight sections and bends

Materials and methods. One of the challenging methods to improve the reliability of power equipment is electric arc spraying. The V.Karpenko Physico-Mechanical Institute of the NAS of Ukraine together with LLC «REZON» developed a technology for protection of heating elements of thermal power plants from ash wear and gas corrosion [19, 20], which involves the deposition of scarcely-alloyed electric arc coatings of the flux-cored wire on the surface of waterwall tubes and tubes of feed-water economizers in order to effectively protect them from ash wear and gas corrosion at operating temperatures of up to 600 °C. This technology allows increasing life of the protected tubes. The use of metallization will allow:

- providing corrosion and erosion resistance to tube sections at elevated temperatures;
- not increasing the total weight of heating surfaces;
- not complicating the access to separate packages of coils;
- not complicating visual observation of the outer surface of tubes also in the locations of spacing bars;
- reducing the labour consumption of the proposed measures by eliminating operations for the manufacture of shells, assembly of welded joints for sealing rings.

Table 1. Mechanical characteristics of tubes before metallization

σ_t, MPa	δ, %	ψ, %
50.3	28.8	60
According to the requirements of TU 14-3-460:2009/TU U 27.2-05757883-207:2009 «Seamless steel tubes for steam boilers and pipelines»		
420–560	24	45

Table 2. Structural characteristics of tubes before metallization

Specimen	Score of the Widmanstaetten structure according to the scale of TU 14-3-460	Score of banding orientiaion according to the scale of TU 14-3-460	Graffitization score in accordance with 3 SOU-N EE 20.321:2009
Cut from FWE	0	0	1 (graphitization was not detected)

Therefore, the use of metallization is the most advantageous method of protecting tubes of heating surfaces. The heat resistance of the metal of the Fe–Cr–B–Al alloying system is provided by the formation of Al_2O_3 oxide film on its surface, which is characterized by high chemical and thermal stability. At elevated temperatures, the diffusion of oxygen and nitrogen into the transition layers leads to the formation of iron Fe_2O_3 oxides and aluminium AlN nitrides, which reduces the heat resistance of coating. In order to mitigate the negative effect of these oxides, silicon is introduced into the coating system, which promotes the formation of a diffusion layer of SiO_2, preventing the oxidation of the subscale layer. The wear resistance of coating is provided by the content of fine iron-chromium carbides $(Fe, Cr)_7O_3$ and spinels $(Fe, Cr)_2O_3$ in the coating. To restore worn-out and protect the new most vulnerable sections of FWE tubes (Figure 5) of the boiler TPP-210A in the conditions of power engineering production of Ukraine, the technology of electric arc metallization was tested.

The technological stages of thermal spraying included the following operations:

- preliminary preparation of the base metal surface;
- spraying;
- external inspection and quality testing of the geothermal heat pump.

To provide a high-quality sprayed layer in accordance with the recommendations [10], the following parameters were tested:

- condition of the tube surface;
- distance of material deposition;
- inclination angle of the torch tip to the sprayed surface of the tube element;
- surface temperature of the base metal in the process of spraying;
- uniformity of coating thickness;
- feed rate of the sprayed material.

Electric arc compressed air jet spraying of heating surfaces was carried out at two thermal power plants in 2013. FWE Coils, which were once in operation at the unit No.2 of the Trypillia TPP (TpTPP) after two years of operation were disassembled and subjected to spraying by metallization. Before spraying, reference specimens were cut out from the tubes to determine mechanical and metallographic properties of the metal of the coils that were in operation. The results of mechanical tests to determine the tensile strength were shown in Table 1.

While carrying out metallographic analysis, the examinations were carried out around the whole perimeter of the tube at a magnification of ×100 and ×500. The ferritic-pearlitic structure of the metal over

Table 3. Composition of sprayed layer

Number of specimen	Content of alloying elements,%								
	Fe	Cr	Al	Si	Ni	Cu	Ti	Zn	Mo
1	76.04	11.76	5.41	5.36	0.17	0.08	0.14	0.13	0.05
2	77.39	11.27	5.58	4.66	0.15	0.09	0.11	0.1	0.09
3	75.13	11.33	5.52	5.67	0.19	0.09	-	0.04	-
4	76.95	12.37	6.04	3.5	0.18	0.11	0.11	0.06	0.04

the whole cross-section of the examined specimen was the same. The results are given in Table 2.

During the mechanical and metallographic tests of tube specimens, no deviations from the standard requirements [21] were found, after which it was decided to apply a protective coating by metallization. The works on coating were carried out on the repair site of the TpTPP and Zmiivska TPP according to the developed procedure [22]. To perform works on applying a protective coating on the tubes of heating surfaces, a set of equipment was used, which included: apparatus for sandblast treatment, electric arc metallizer, filter drier, cassettes with flux-cored wire, electrical cabinet, power source. In the process of spraying, an in-process control was performed, in which the quality of preparation of heating surfaces for spraying was subjected to testing, mode of spraying, order of applying layers of sprayed metal, granularity and color of the coating were subjected to testing. Spraying was performed without the use of a substrate. The tubes after metallization were not subjected to heat treatment.

After spraying of the protective layer, the coils were mounted on the steam boiler of supercritical pressure TPP-210 A, station unit No. 1, block A. According to the project for the boiler TPP-210 A, as a fuel, the coal of grade ASh was used. During operation of the boiler on the coal of grade ASh, the temperature of gases in the zone of the coils location was within 700–900 °C, and the composition of the furnace gases was approximately the following: CO – 50–70 mg/m^3; O_2 – 5 %; SO_2 – 2863 mg/m^3; NO_x – 1187 mg/m^3. Chemical composition of coal ASh ash from cyclone ash collectors (%): SiO_2 = 51.4, CaO = 3.8, MgO = 1.6, Fe_2O_3 = 15.3, Al_2O_3 = 22.4, K_2O = 3.3, Na_2O = 1.5. At the Uglegorsk TPP (Ugl.TPP), two heating surfaces were subjected to spraying: steamer (St. 12Kh1MF) between the spacing bars and bends near the walls of the steam boiler of supercritical pressure TPP-312 A, station unit No.4. Similarly, FWE (steel 20 (st.)) of the steam boiler of supercritical pressure TPP-312 A, station unit No.2 was subjected to spraying. According to the project for the boiler TPP-312 A, as a fuel, the coal of grade G was used. It was found that at the Tp.TPP and Ugl.TPP, the main type of wear on FWE was ash wear, and between the spacing bars — corrosion wear. Therefore, spraying on the heating surfaces was performed by one and the same material. The composition of the spray layer is given in Table 3. At the Trypillian TPP, the composition was tested by the X-ray fluorescent spectrometer NITON XL2.

Electric arc spraying was carried out in 2013 on the most abrasive-worn sections of coils of FWE boilers TPP-210 A and TPP-312 A, corrosion-damaged sections of coil of steamer tubes in the spacing bars of the boiler TPP-312 A (low pressure). Photos of sprayed coils are shown in Figure 6.

After spraying and during operation, the cuts from the heating surfaces of tubes were performed, whose microstructure should meet the requirements [21] for reliable operation. At the Uglegorsk TPP after metallization, for metallographic examination from the sprayed steamer (low pressure) tube 2 reference specimens were cut out: one — directly from the bend (with spraying on the surface), and the second one (reference) — at a distance of 150 mm from the

Figure 6. Appearance of sprayed coils

Figure 7. Appearance of tube bend and its surface after spraying

sprayed zone. The sections were made by successive grinding and polishing. The etching of sections was performed in a 4 % solution of nitric acid in ethyl alcohol. For metallographic analysis, the microscope MIM-8M was used at a magnification of ×100 and ×500 times. The structure of the reference specimen is a ferrite-pearlite. Styloscopy was performed in a stationary styloscope SL-13. To external inspection, sprayed tubes and bends were subjected. Mechanical tests were carried out on flattening and determination of mechanical properties. At the Trypillia TPP after carrying out metallization of FWE coils with a diameter of 32×6 mm St.20, coils (production specimens) were cut out. Then, specimens were cut out of them, which were tested on flattening. Delamination of the coating layer occurs after bringing together the inner sides to H_{in} = 15 mm. Bringing of the sides together was performed up to H_{in} = 10 mm. The sprayed layer was subjected to measuring hardness in the ultrasonic hardness meter TKM-459.

At the Trypillia TPP, two variants of welding steel tubes after metallization were investigated. The first is an electric arc welding of tubes after metallization by 2.5 mm TsU-5 electrodes with the tubes that did not pass metallization. The second is welding by TsU-5 electrodes during alignment of tubes between each other that passed metallization. Welding was performed in accordance with [23]. Before welding the edges of tubes were treated at an angle of 40–45° with cleaning in the region of ends. Diameter of the rod of TsU-5 electrodes is 2.5 mm. According to the appearance, the welds are in a satisfactory condition. Cracking, pores, cavities, undercuts and other outer defects were not observed. The surface layer of tubes with metallization in the area of welded joint are cleaned for testing using non-destructive methods. Ultrasonic testing did not detect inner defects in the butt welds. Microstructure of metal in the near-weld zone and in the welds area in both cases is satisfactory. When conducting X-ray fluorescent analysis of welded joints, a slight increase in chromium content was revealed. An increased silicon content in welded joints is obviously associated with insufficient quality preparation. During mechanical tests of the weld, the fracture of the specimen occurs mainly over the base metal, indicating satisfactory mechanical properties of the weld. Microstructure of metal in the near-weld and weld zone in both cases is within the normal limits.

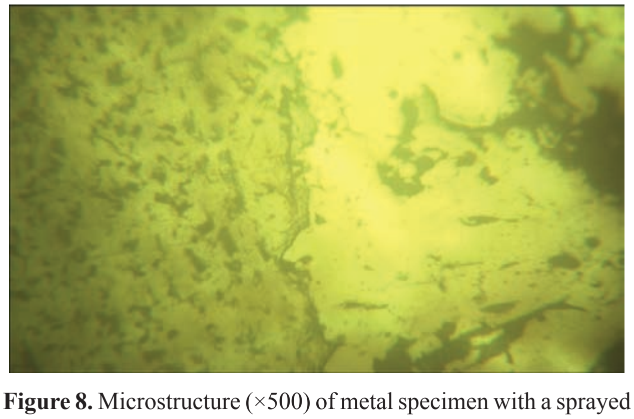

Figure 8. Microstructure (×500) of metal specimen with a sprayed layer

Results and discussion. The inspection of tubes and bends showed that the sprayed layer has a rough surface with a metallic luster. At a detailed consideration of surface sprayings, separated large crystals are distinguished on it, which give it a significant roughness. Spraying has a uniform and solid distribution over the outer surface of the bends. As a result of performed spraying of tubes and bends at the Trypillia TPP, the photos of their macrostructure (Figure 7), as well as microstructure of the tube after spraying were made (Figure 8). The structure after metallization did not undergo changes and complied with the standard requirements.

With the help of high-quality spectral analysis, it was found that a sprayed protective layer of FWE tube, produced by the method of electric arc metallization, represents a composite with a strengthening carbide phase in a metal matrix and contains such alloying elements as chromium and aluminium. The composition of the carbide phase is about 40 %. The base metal is carbon steel (alloying elements were not detected). In the microstructure of sprayed tubes from steel of grade 20 (Figure 9), the orientation on

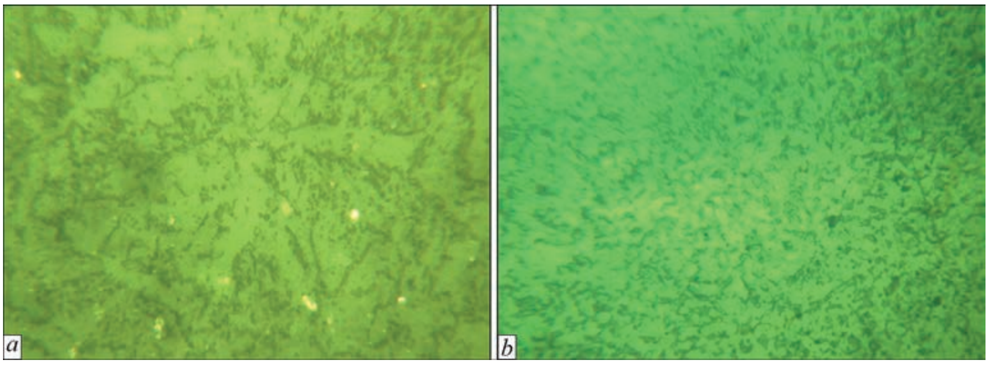

Figure 9. Microstructure of sprayed tubes from steel of grade 20: *a* — ×500; *b* — ×100

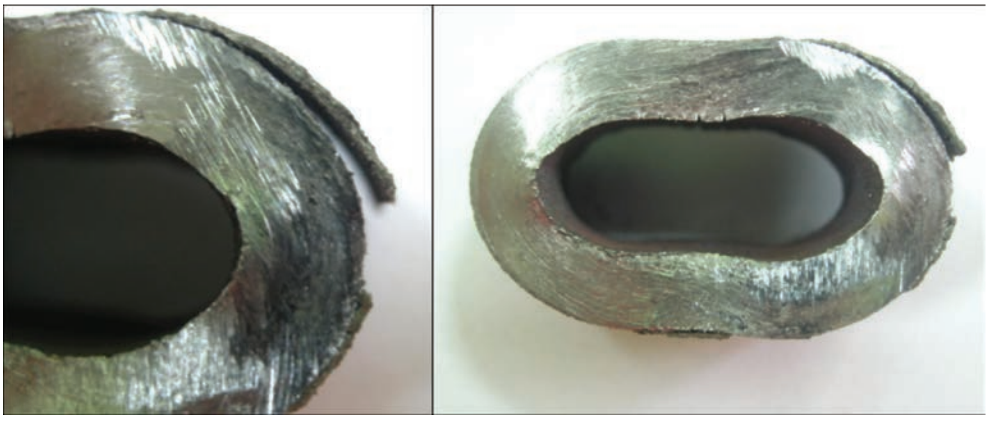

Figure 10. Specimens after tests on flattening

the Widmanstatten structure should not exceed the 3rd point of the scale of the 2nd Appendix B «Scales of banding orientation and Widmanstatten structure of boiler tube metal» [21].

When conducting metallographic examination of steamer tubes of the Uglegorsk TPP it was found that the initial structure of the tube metal is characterized by a significant banded orientation, which is a deviation from the standards and indicates a poor thermal treatment of tubes after rolling in the process of their manufacture. The structure of the sprayed specimen is ferrite-pearlite as in the reference one; visible structural changes were not found. Under the sprayed layer, a narrow borderline band of the base metal with a thickness from 0.07 to 0.15 mm is seen, which was subjected to interaction with a sprayed layer. The structure of the matrix of this band is the same as in the base metal — ferrite-pearlite. Within this band, the used etcher did not provide the inclusions of the sprayed material. However, it can be assumed that diffusion inclusions should be present in it.

The used etcher was not able to reveal any structural components in the structure of spraying (special chemical reagents were not used). However, it allowed establishing a loose-layer and porous (not monolithic) structure of spraying, caused by the technological

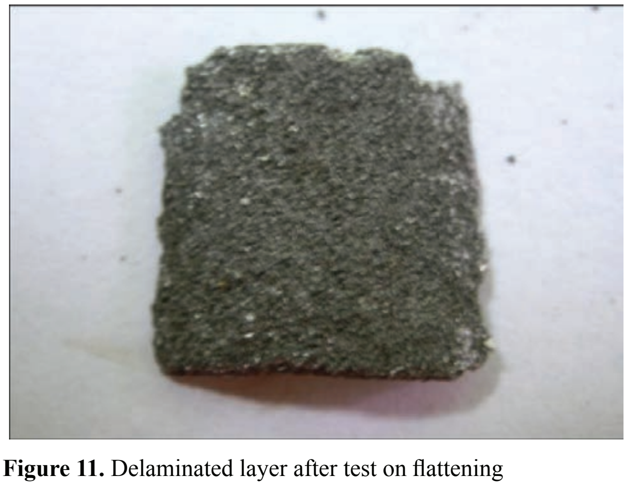

Figure 11. Delaminated layer after test on flattening

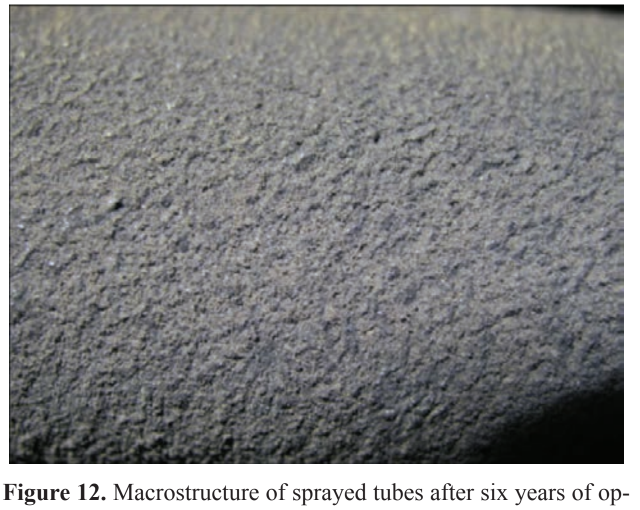

Figure 12. Macrostructure of sprayed tubes after six years of operation

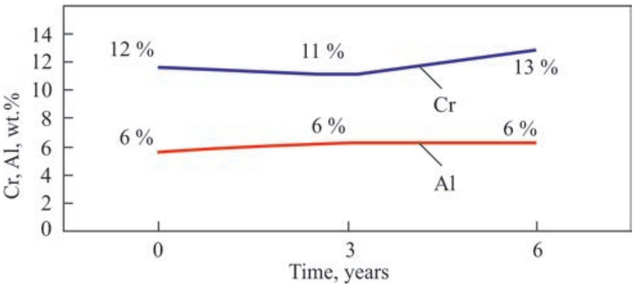

Figure 14. Change in the concentration of chromium and aluminium in the surface coating layer depending on service life

features of electric arc metallization. In both cases, the thickness of the sprayed layer varies in different sections of the tube. Thus, in the frontal point of the tube, the thickness of spraying reaches 0.42 mm, and on the side points it amounts to 0.2 mm. Taking into account the boundary layer of the base metal, which was subjected to diffusion of the sprayed material in it, it can be stated that the largest spraying thickness is 0.57 mm (on the frontal part of the bend). When carrying out technological tests on flattening cracks, tears over the base metal of the tube were not detected. After tests on flattening (Figure 10) for a delaminated layer (0.55 mm) (Figure 11), the X-ray fluorescence analysis was conducted, which showed the following chemical composition, wt.%: 11.7–12.21 Cr; 0.12 Ni; 4.0–5.65 Si; 4.37–5.87 Al; 0.37–0.44 S. Photo of the macrostructure of sprayed tubes after six years of operation is shown in Figure 11.

Destruction of the surface layer occurs by a delamination of large fragments of the sprayed layer. During mechanical tests for determining the tensile strength of the tube after spraying, the results were obtained given in Table 4.

The obtained results of mechanical tests meet the requirements of TU 14-3-460: 2009/TU U 27.2-05757883-207:2009 [21]. The areas of the sprayed layer has the hardness *HRC* 54–58. The surface layer under the delaminated coating has the following chemical composition, wt.%: 91.47 Fe; 2.78 Cr; 3.9 Si; 1.1 Al; 0.26 S. Hardness of the surface under the spraying layer is *HB* 200–217. Thus, the obtained

Table 4. Results of mechanical tests

σ_t, MPa	δ, %	ψ, %
51.1	28.2	58
TS 14-3-460:2009/TS 27.2-05757883-207:2009		
420–560	24	45

Table 5. Composition of sprayed layer after three-year operation at TPP

Number of specimen	Content of alloying elements, %				
	Fe	Cr	Al	Si	Ni
1	Base	11.41	5.67	5.67	0.15
2	Same	10.89	5.87	5.5	0.17

Table 6. Composition of sprayed layer after six-year operation at TPP

Number of specimen	Content of alloying elements, %				
	Fe	Cr	Al	Si	Ni
1	Base	12.9	6.67	7.9	0.1
2	Same	12.7	5.79	7.1	0.1

results may indicate that the base metal after spraying did not undergo significant changes in microstructure and mechanical properties and corresponded to the requirements of technical conditions. After a three-year operation of tubes and bends at the Trypillia TPP, a spectral analysis of the coating surface layer. Layer composition was changed insignificantly (Table 5).

When carrying out cuts after six years of operation, macro- and microstructure of sprayed tubes (Figures 12, 13), the composition of the surface layer were also recorded (Table 6). Technological tests on flattening, the measurement of hardness was not carried out. During operation, the surface becomes more rough, on the surface protruding carbides of different size are visible.

Examination of microstructure before and after the wear in the flow of a coal dust at the operating parameters of FWE show reorientation of the carbide frame in the matrix.

The surface diffusive layer has the following chemical composition, wt.%: 3.27 Cr; 1.87 Si; 0.9 Al; 0.3 S.

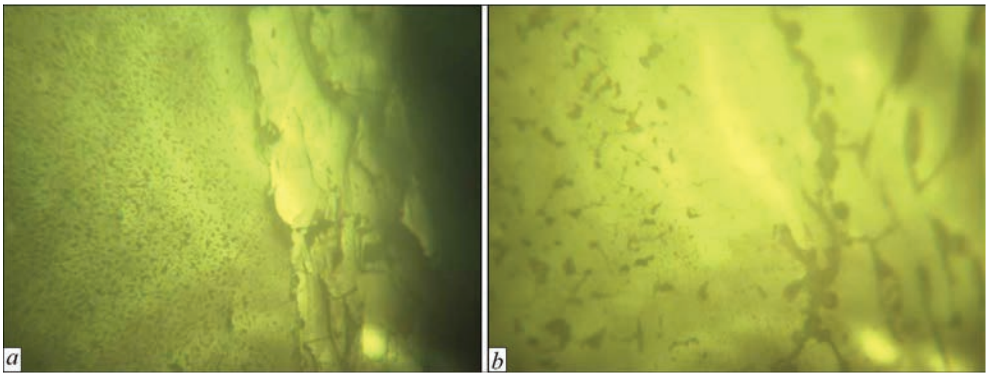

Figure 13. Microstructure of sprayed tubes after six years of operation: *a* — ×100; *b* — ×500

Table 7. Data from thinning of tube walls

Number of unit	Heating surface	Surface, working environment	Grade of material	Number of coil	Number of tube	Thinning, mm				Service life, h
						Left side	Right side	Outer	Inner	
1	FWE	ASh	St.20	152	1	–0.4	–0.4	–0.5	+0.2	11296
1	FWE	Same	Same	150	Same	–0.5	–0.5	–0.8	+0.1	12138
1	FWE (after spraying)			151		+0.4	+0.5	+0.7	+0.2	9084

Horizontal lines in Figure 14 show that during six years, the concentration of chromium in the surface layer almost did not change and even slightly increased, its accumulation in the surface layer occurs. An increase in the concentration of aluminium in the surface layer is most likely associated with precipitation of aluminium-containing elements, formed in the process of combustion of organic fuel on the tubes of coils.

Destruction of the surface layer during testing of specimens occurs by cracking of the coating into tiny fragments and its spalling. As is seen, the exposure of coatings at operating parameters leads to a change in the mechanics of their fractures, which is possibly caused by the change in the structure of the disperse phases. It was impossible to measure the hardness of the sprayed layer. The hardness of the surface under the spraying layer is *HB* 180. At each power plant, data from the actual thickness of the walls of the tubes of heating surfaces are collected, applying destructive and nondestructive methods. When carrying out cuts from tubes, data from tube thickness, microstructure and mechanical properties are fixed. To measure thinning of tubes, the procedure of direct measurement of the thickness of the wall is used. The summary data from thinning of the walls of tubes before spraying, as well as the time of each cut specimen are summarized in Table 7.

Analyzing data from thinning, it can be concluded that in all cases, with an increase in the operation time, the value of thinning the wall from the ash wear grows as well. The greatest intensity of the ash wear is observed on the first two tubes of steel 20 of extreme FWE coils. This phenomenon is most likely associated with a designing feature of the gas tract of a coal-dust Π-shaped boiler. At the outlet from the upper radiation part, in a rotary chamber, the gases change their direction and the largest particles of fuel combustion products are thrown into the periphery of the general flow. An increase in their density in the flow contributes to the intensification of the ash wear of 20 extreme FWE coils [24]. After metallization of the surface of tubes of FWE coils, a decrease in the intensity of the ash wear of the coils was revealed. While measuring the thickness of the wall on the reference cuts, thinning was not recorded. Thus, in this case, it is possible to allow the presence of the influence of hardness on the rate of ash wear and conclude that with an increase in hardness wear resistance grows. This observation is agreed with a model of erosion wear [23].

CONCLUSIONS

In the work, the use of the method of electric arc spraying (metallization), performed by LLC «Rezon» to improve the reliability of the power equipment of TPP, was studied. According to the obtained data on mechanical, chemical and structural state of the tube metal and the coating layer, it can be concluded about the positive experience of introducing a method of electric arc spraying as a promising and highly effective method for increasing the reliability of power equipment. At the Trypillia TPP, two variants of welding tubes of steel 20 after metallization were investigated. The first is an electric arc welding of tubes after metallization by TsU-5 electrodes of 2.5 mm with the tubes that did not pass metallization. The second is welding by TsU-5 electrodes during alignment of tubes that passed metallization, with each other. When carrying out X-ray fluorescence analysis of welded joints, a slight increase in chromium content was revealed. An increased content of chromium in the welded joint is obviously associated with insufficient quality of surface preparation. During mechanical tests of the weld, fracture of the specimen occurs mainly over the base metal, indicating satisfactory mechanical properties of the weld. Microstructure of metal in the near-weld and weld zone in both cases is within the norm [21]. A lack of corrosion damages in the places of mounting the studied coils and a significant erosion wear of the FWE tube walls, as compared to untreated spraying, with conventional methods of individual protection of coils, indicates a successful realization of the technology, as is evidenced by an increase in the life of the boiler tube.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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