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GAS-POWDER SPRAYING AS A HIGH-EFFICIENT METHOD OF INCREASING THE OPERATION RELIABILITY OF POWER EQUIPMENT

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In the work the spraying is suggested as the promising and high-efficient method for improvement of operation reliability of TPP power equipment. As the main type of wear of pipe elements of TPP power equipment is the ash wear and corrosion, then to increase their reliability, service life and working capacity it is suggested to apply the electric arc spraying using material PP 70Kh10R3Yu5 as a method of thermal modification of heating surfaces. The aim of the work is the investigation of efficiency of spraying application for improving the operation reliability of TPP power equipment. Spraying of heating surfaces was carried out in two thermal power plants of PJSC «Centrenergo» in 2013. A feasibility study showed that the implementation of spraying technology allows 1.5–2.0 times decreasing the expenses as compared with losses, incurred by TPP in case of emergency shutdowns, and increasing the service life of the equipment approximately by 1.4 times. 15 Ref., 7 Tables, 12 Figures.

Keywords: *spraying, power equipment, pipes, bends, reliability, boilers, economizer, thermal power plant*

The intensive wear of heat-exchange surfaces of boilers of thermal power plants (TPP), in particular, water-wall tubes and pipes of economizers, is caused by use of a coal dust with a large part of hard incombustible impurities [1–3]. Analysis of damages by the classification features [4] shows that the main cause of damage of boiler pipes is a corrosion-erosion wear. From the data of work [5], its share on separate units reached 60 %. Coiled pipes of water economizers are mostly often subjected to erosion. The abrasive ash particles, trapped by smoke gases, strike againts the surface of pipes at high rate and cause an ash wear (Figure 1). At the surface of water-wall tubes of steel 12Kh1MF at elevated temperatures up to 585 °C the films of iron oxides are formed, which have a weak adhesion with a steel surface and they are easily worn-out by abrasive particles. The wear of outer pipe surface occurs nonuniformly over a large area, it is localized in definite places and when reaching the critical thickness of pipe wall its burst takes place, which leads to the power unit shutdown. The thermal load to the outer pipe wall is also increased due to sedimentation of salts on inner surfaces of water-wall tubes, which, in addition, undergo the corrosion-erosion damages. Therefore, the development of new effective methods of improving the operation reliability of power equipment of TPP is the urgent direction.

Figure 1. Nature of damage of 32×6 mm diameter pipe of water economizer as a result of ash wear effect

The damage of pipe elements of heating surfaces of TPP power equipment have a nature of creep mechanisms with a fatigue pronounce, proceeding of processes of erosion and gas corrosion (oxidizing) due to extremely-high conditions of service, connected with high values of temperature, available cyclic loads and aggressive working environment, as well as due to abrasive action of combustion products of the coal fuel [2, 3].

Analysis of methods of improving the operation reliability of power equipment. As the main type of wear on water economizer (WE) of TPP boilers is an ash wear, and corrosion between the distance-type straps, then in works [3, 6] an integrated solution of the problem of extension of the service life of water-wall tubes of boilers and pipes of economizer due to development of new heat-resistant and wear-resistant thermal coatings was suggested. As a result, in structure of such coatings during the service of boiler tubes and pipes of economizers the dispersion processes of strengthening due to precipitation in metal of fine-dispersed phases of carbides, nitrides and intermetallics, will be proceeding, which will increase greatly their service properties in operation.

It is shown in works [7, 8], that it is possible to apply surfacing for improvement of operation reliability of power plants equipment in ash and corrosion wear. The presently developed powder self-fluxing wear-resistant and anticorrosion alloys, as well as the technologies of their deposition allow producing the metallic coatings with preset properties on the surface of parts. The gas-powder surfacing using self-fluxing wear-resistant alloys found a wide application in restoration of worn-out pipe regions and protection of new ones in water-wall economizers of boilers at the unitized TPP.

The modern industry has in its disposal a large selection of special powders for surfacing and spraying, which impart the various properties to surface being sprayed, including also an abrasive wear resistance, corrosion resistance, wear resistance at elevated temperatures and aggressive environments. These are powders on the base of chromium, nickel and carbide-forming elements.

As a protective coating the metallic powder PG-SR of grade PR-N80Kh13S2R TUN-1-3785–84 of fraction «OM» or powder PR-N77Kh15S3R2 (PG-12N-02) [9], fused as a result of coating deposition, are used. The powder deposition of pipe elements of boiler heating surfaces is performed during surfacing in several layers with a different thickness and width. The selection of required characteristics of a protective layer is made by the surfacing modes. This allows increasing their service life by 10–15 years.

In work [3] for restoration and protection of pipes and elements, which were subjected to the ash wear, the welding technologies are used, at which the restoration treatment of a thin region of a pipe element of steel 20 of water-wall economizer is performed by the manual arc (argon arc) welding. The application of the manual arc welding in case of surfacing of pipe elements of economizers of boilers envisages the use of electrodes E50A for steel 20 and E-09Kh1MF for steel 12Kh1MF. For manual argon arc welding the filler wires Sv-08GS and Sv-08G2S for pipes of steel 20, Sv-08KhM for pipes of steel 12KhMF with service temperature up to 510°C and Sv-08KhMFA for pipes of steel 12Kh1MF with service temperature above 510 °C are used.

Also, on water economizers of TPP boilers the individual collars are used to protect bends and straight pipe regions, subjected to wear (Figure 2).

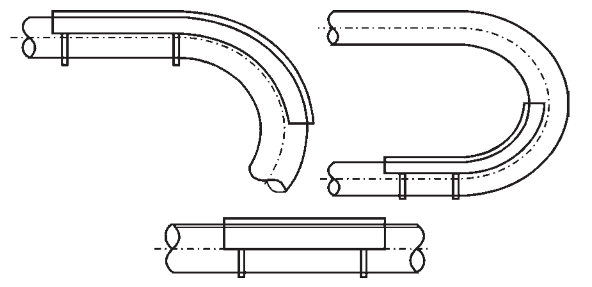

Figure 2. Individual collars for protection of bends and straight regions of pipes of a water economizer of TPP boilers

Undoubtedly, the given method allows increasing the service life and reliability of pipe operation, however, the application of collars for protection of pipes of heating surfaces in places of distance-type straps location is not rational due to a local increase in section, as the collars do not possess special properties for pipes protection from the corrosion-erosion effect. The corrosion-erosion processes will be proceeding in any case, and the additional increase in pipes weight (due to collars application) will increase the load on coiled pipes, which was not taken into account in designing, that can influence the workability of welded joints (cracks in welded joints and HAZ, pinchings). Moreover, due to application of collars the local increase in pipe diameter occurs, resulting in decrease of a passing section for fuel gases between the separate pipes, which deteriorates the aerodynamics of gas flows and leads to increased wear of pipes of the neighboring coiled pipes, complicates access to separate packs of coiled pipes and reduces their maintainability.

The corrosion developing can be seen in a technological gap of an overlap joint (between pipes), and the presence of collar outside do not allow making required inspection of pipe metal state under it.

It was suggested to apply a local gas-powder spraying with special metallic coatings to provide local protection of pipes under the distance-type straps [10].

The drawbacks of the above-given methods of gas-powder and arc surfacing are the high heat inputs, which can cause a possible distortion of coiled pipes, structural changes in ferrite-pearlite structure of steel and high requirements specified to the welder qualification.

One of the promising methods of increasing the operation reliability of power equipment is the electric arc spraying.

V. Karpenko Physical-Mechanical Institute of the NAS of Ukraine has developed the technology of protection of heating elements of thermal power plants from the abrasive wear and gas corrosion [11], which envisages the deposition of scarcely-alloyed electric arc coatings from flux-cored wire to the surface of water-wall tubes and pipes of economizers of thermal power plants for their effective protection from the abrasive wear and gas corrosion at service temperatures up to 600 °C. This technology allows twice increasing service life of protected pipes.

Table 1. Mechanical characteristics of pipes before metallization

σ_t, MPa	δ, %	ψ, %
50.3	28.8	60
According to requirements of TS 14-3-460:2009/TS U 27.2-05757883-207:2009 «Steel seamless pipes for steam boilers and pipelines»		
42–56	24	45

The application of metallization will allow:

● imparting the corrosion-erosion resistance to pipe regions at elevated temperatures;

● not increasing the total weight of heating surfaces;

● not hindering the access to separate packs of coiled pipes;

● not hindering the visual inspection of outer surface of pipes in places of location of the distance-type straps;

● decreasing the labor consumption for suggested measures due to elimination of operations for manufacture of sleeves, assembly of welded joints for collars.

So, the application of metallization is the most profitable method for protection of pipes of the heating surfaces.

The aim of the present work is the investigation of application of electric arc spraying (metallization) for improving the operation reliability of TPP power equipment.

Grounding the selection of alloying system and flux-cored wire. The heat resistance of metal of alloying system Fe–Cr–B–Al is provided by the formation of oxide film Al_2O_3 on its surface, which is characterized by a high chemical and thermal stability. At elevated temperatures the diffusion of oxygen and nitrogen into transient layers leads to the formation of iron oxides Fe_2O_3 and aluminium nitrides AlN, which reduces the coating heat resistance. To soften the negative effect of the mentioned oxides, the silicon is added into the coating system, which promotes the formation of a diffusion layer SiO_2, preventing the oxidation of an under-scale layer. The wear resistance of coating is proved by the content in the coating composition of fine-dispersed iron-chrome carbides $(Fe, Cr)_7$, C_3, spinels $(Fe, Cr)_2O_3$.

Procedure. The electric arc spraying in a compressed air jet of heating surfaces was performed at two thermal power plants of PJSC «Centrenergo» in 2013. The coiled pipes of water-wall economizers of Tripolskaya TPP (TrTPP), having two-year service in unit No.2, were dismantled and subjected to spraying by the metallization method. Before spraying the test specimens were cut out from pipes, being in service in coiled pipes, for determination of mechanical and metallographic properties of metal. Results of mechanical tests for determination of tensile strength are given in Table 1.

During carrying out of metallographic analysis the investigations were performed around the whole perimeter of the pipe at magnification ×100 and ×500. Ferrite-pearlite structure of metal across the whole section of test specimen was similar. Results are given in Table 2.

Table 2. Structural characteristics of pipes before metallization

Microstructure	Number of structure by scale TS 14-3-460	Number of striation by scale TS 14-3-460	Number of graphitization acc. to SOU-N EE 20.321:2009
Cut-out from WE	0	0	1 (graphitization was not revealed)

During carrying out of mechanical and metallographic tests of pipe specimens the deviations from standard requirements [12] were not revealed, and then the decision was taken about the deposition of protective coating by the metallization method.

The works on coating deposition were carried out at the repair platform of TrTPP in accordance with the developed procedure [13].

The preparation of pipe elements for metallization consisted of cleaning and activation of the surface by the method of sand blasting treatment. The quality of preparation of pipe elements for spraying was visually inspected.

To perform works for deposition of the protective coating on pipes of heating surfaces a set of equipment was used, consisting of: machine for sand blasting treatment, electric arc metallization device, filter-moisture separator, cassettes with flux-cored wire, electric cabinet, power source.

During spraying the in-process control was made, which included checking of the quality of preparation of heating surfaces for spraying, spraying mode, sequence of deposition of layers of metal being sprayed, granularity and coating color. The spraying was carried out without using of substrate. The pipes after metallization were not subjected to heat treatment.

After spraying of a protective layer the coiled pipes were mounted on a steam boiler of a supercritical pressure TPP-210 A, power plant unit No.1, building A. As a fuel, coal of grade ASh was used according to the project for boiler TPP-210 A.

At Uglegorskaya TPP (UgTPP) two heating surfaces were subjected to spraying: KPP n.p. (steel 12Kh1MF) between distance-type straps and bends near walls of steam boiler TPP-312 A of supercritical pressure power plant unit No.4. Also, the water-wall economizer (steel 20) of steam boiler of supercritical pressure TPP-312 A of power plant unit No.2 were subjected to spraying. According to the project as a fuel for boiler TPP-312 A the coal of grade G was used. It was found that at TrTPP and UgTPP the

Table 3. Composition of sprayed layer

Specimen number	Content of alloying elements, wt.%								
	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

main type of wear on water-wall economizer was an ash type, and between the distance-type straps was a corrosion one, therefore the spraying on the heating surfaces was carried out by the same material, namely flux-cored wire PP 70Kh10R3Yu5.

The composition of the sprayed layer is given in Table 3. At Tripolskaya TPP the composition was controlled by the X-ray fluorescent spectrometer NITON XL2.

The electric arc spraying was carried out in 2013 at the most abrasively worn-out regions of coiled pipes of the water-wall economizer of boilers TPP-210 A and TPP-312 A, corrosion-damaged regions of coiled pipes KPP n/p in distance-type straps of boiler TPP-312 A.

The appearance of sprayed coiled pipes is given in Figure 3.

After the spraying and during service the cut-outs from pipes were made of heating surfaces, the microstructure of which should correspond to the requirements for safe service [12].

At Uglegorskaya TPP after metallization 2 reference specimens were cut out from the sprayed pipe KPP n.p. for metallographic examination: one was cut out from a bend (with spraying on surface) and another one (reference) was cut out at the distance of 150 mm from the sprayed zone. Sections were manufactured by a successive grinding and polishing. Etching of sections was made in 4 % solution of nitric acid in ethyl alcohol. For metallographic analysis the microscope MIM-8M was used at magnification ×100 and ×500. Structure of reference sample was ferrite-pearlite.

Steeloscoping was made at the stationary steeloscope SL-13. Sprayed pipes and bends were subjected to visual inspection. Mechanical tests were carried out for flattening and determination of mechanical properties.

At Tripolskaya TPP after metallization of coiled pipes of water-wall economizer of Ø32×6 mm of steel 20 the coils were cut out (industrial specimens), then the templates were cut out from them, which were tested for flattening. Delamination of coating layers occurs after convergence of inner sides up to H_{in} = 15 mm. Convergence of sides was made up to H_{in} = 10 mm. The sprayed layer was subjected to hardness measurement in the ultrasonic hardness meter TKM-459.

Results of investigation. Visual inspection of pipes and bends showed that the sprayed layer has a rough surface with a metallic glittering. During the detailed inspection of the sprayed surface the separate large crystals are seen, which impart the roughness to the surface. The spraying has a uniform and continuous distribution over the outer surface of bends. Figure 4 shows the appearance of pipe bend and macrostructure of its surface, and Figure 5 presents microstructure of pipe surface. The structure after metallization did not subjected to changes and corresponded to the standard requirements.

The quality spectral analysis showed that the sprayed protective layer of pipe of the water-wall economizer, 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 content of

Figure 3. Appearance of sprayed coiled pipes

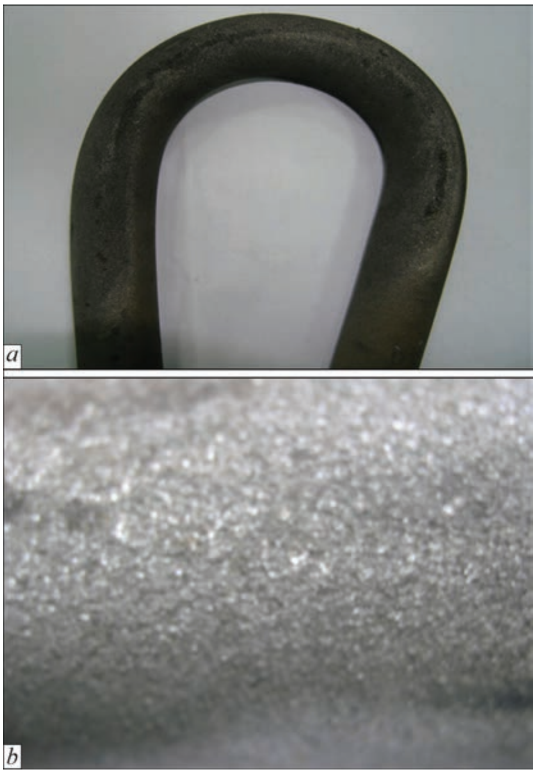

Figure 4. Appearance of pipe bend (*a*) and macrostructure of its surface (*b*)

a carbide phase was about 40 %. The base metal is a carbon steel (alloying elements were not revealed).

In the microstructure of sprayed pipes of steel 20 (Figure 6) the orientation by Widmanstatten structure should not exceed the third point of scale 2 of Appendix B «Scales of striation and Widmanstatten structure of metal of boiler pipes».

During metallographic examinations of pipes KPP n.p. of Uglegorskaya TPP it was found that a pronounced segregation banding is characteristic for initial metal structure, that is a deviation from standards and testifies the nonquality heat treatment of pipes after rolling in the process of their manufacture. Structure of sprayed specimen is the same as in the reference specimen, i.e. ferrite-pearlite. Visible structure changes were not found.

Under the sprayed layer a narrow boundary band of base metal of thickness from 0.07 up to 0.15 mm is seen, which was subjected to interaction with a

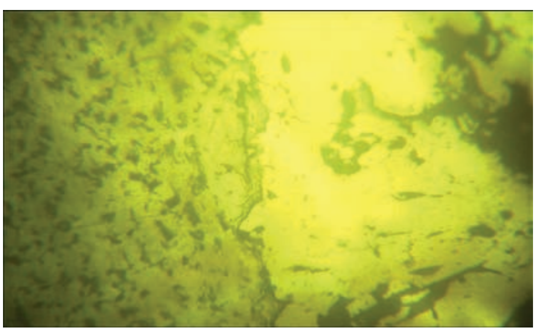

Figure 5. Microstructure (×500) of sprayed layer

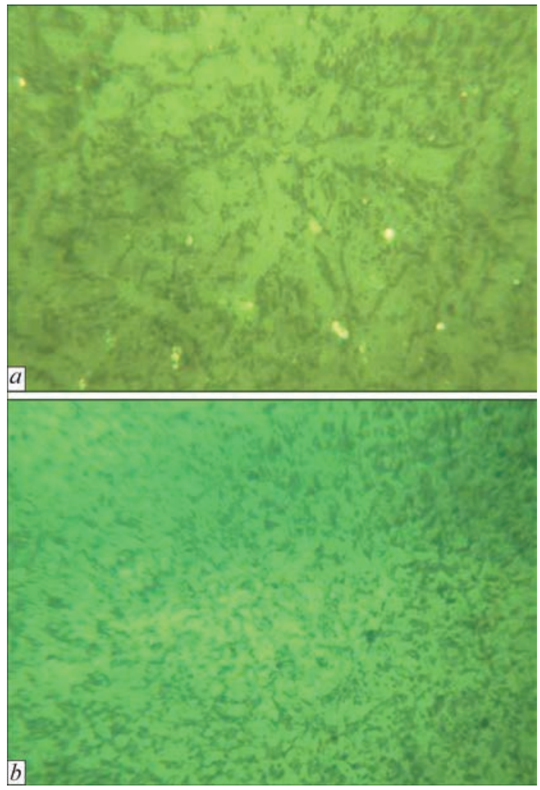

Figure 6. Microstructure of sprayed pipes of steel 20: *a* — ×500; *b* — ×100

sprayed layer. The structure of matrix of this band is the same as in base metal, i.e. ferrite-pearlite. Within the limits of this band the used etching agent did not distinguish clearly the inclusions of sprayed material. However, it is possible to assume that the diffusion inclusions should be present there.

The used etching agent could not distinguish any structural components in the structure of sprayed metal (special chemical reagents were not used). However, it allowed detecting the loose-laminar and porous (nonmonolithic) constitution of spraying, which is caused by technological features of the electric arc metallization.

In both cases the thickness of the sprayed layer is varied at different pipe regions. Thus, in frontal place of pipe the thickness of spraying reaches 0.42 mm, and on the sides — up to 0.2 mm. With account for the boundary layer of base metal, which was subjected to sprayed metal diffusion into it, it can be stated that the largest thickness of spraying is 0.57 mm (at the bend frontal part).

During technological tests for flattening the cracks, tears in the pipe base metal were not revealed. After tests for flattening (Figure 7) the X-ray fluorescent analysis was made for separated layer (0.55 mm) (Figure 8), which showed the following chemical composition: 11.7–12.21 % Cr; 0.12 % Ni; 4.0–5.65 % Si; 4.37–5.87 % Al; 0.37–0.44 % S.

The fracture of surface layer occurs by separation of large fragments of the sprayed layer. During me-

Table 4. Mechanical properties of pipe metal after spraying

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

Table 5. Composition of sprayed layer after 30-year service 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

chanical tests for determination of tensile strength of pipe after spraying the results were obtained, which are given in Table 4.

The obtained results of mechanical tests are in compliance with requirements of TS 14-3-460:2009/ TS U 27.2-05757883-297:3009.

The sprayed layer regions have hardness *HRC* 54–58. The surface layer under the separated coating has the following chemical composition: 91.47 % Fe; 2.78 % Cr; 3.9 % Si; 1.1 % Al; 0.26 % S. Hardness of surface under the layer of spraying *HV* 200–217.

Thus, the obtained results can prove, that the base metal after spraying did not undergo the large changes in microstructure and mechanical properties and was in compliance with appropriate technical conditions.

After the 3-year service of pipes and bends at Tripolskaya TPP a spectral analysis of the coating surface layer was carried out. The layer composition was negligibly changed (Table 5).

In making cut-outs after 6 years of service the macro- and microstructure of sprayed pipes (Figures 9, 10), composition of surface layer (Table 6) were also recorded. Technological tests for flattening were performed, hardness was not measured.

Macrostructure of sprayed pipes after 6 years of service is given in Figure 9.

During service the surface becomes rougher, projected carbides of different size are seen on the surface. Examination of microstructure before and after wear in the flow of coal dust at working parameters of the water-wall economizer shows reorientation of carbide frame in matrix. The surface diffusion layer has the following chemical composition: 3.27 % Cr; 1.87 % Si; 0.9 % Al; 0.3 % S.

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

Number of specimen	Content of alloying elements, wt.%				
	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

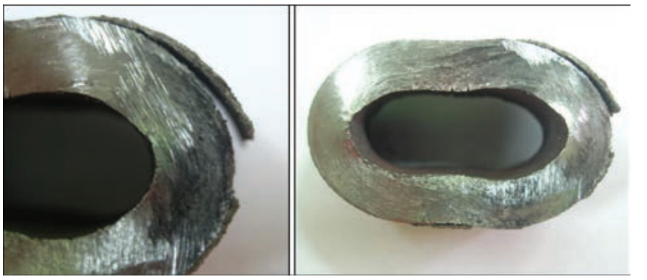

Figure 7. Specimens after tests for flattening

The horizontal nature of line in Figure 11 shows that during 6 years the concentration of chromium in surface layer almost was not changed and even increased a little, its storage in surface layer is occurred. The increase in aluminium concentration in surface layer is largely connected with deposition of aluminium-containing elements, formed in the process of combustion of organic fuel, on coiled pipes.

Fracture of surface layer during testing of specimens is occurred by cracking of coating into fine fragments and its spalling (Figure 12). As we see, holding of coatings at working parameters leads to change in mechanics of their fracture, which is possibly caused by change in structure of dispersed phases. It was not managed to measure the hardness of the sprayed layer. Hardness of surface under the layer of spraying is *HV* 180.

At each power plant the data are collected up by a real thickness of pipe walls of heating surfaces by using destructive and nondestructive methods. In making cut-outs from pipes the data are recorded as to its thickness, microstructure and mechanical properties. To measure the pipe thinning the method of direct measurement of wall thickness is used. The resulted data on characteristic of pipes before spraying, as well during operation of each cut-out specimen are generalized in Table 7.

By analyzing the data on thinning, it is possible to conclude that in all the cases with increase in time of service the value of wall thinning due to ash wear is also increased.

Figure 8. Appearance of separated sprayed layer after test for flattening

Figure 9. Macrostructure of sprayed pipes after 6-year service

The highest intensity of ash wear is observed on the first two pipes of twenty edge coiled pipes of water-wall economizer. This phenomenon, first of all, is connected with a design peculiar feature of gas tract of coal dust П-shaped boiler. At output from URP (upper radiation part), in rotation chamber, gases change their direction and the largest particles of fuel combustion products are coming to the periphery of the general flow. The increase of their density in flow promotes the intensification of ash wear of twenty edge coiled pipes of the water-wall economizer.

After metallization of surface of coiled pipes of water-wall economizer the decrease in intensity of ash wear of coiled pipes was revealed. During measurement of wall thickness, thinning on the reference cut-outs was not observed.

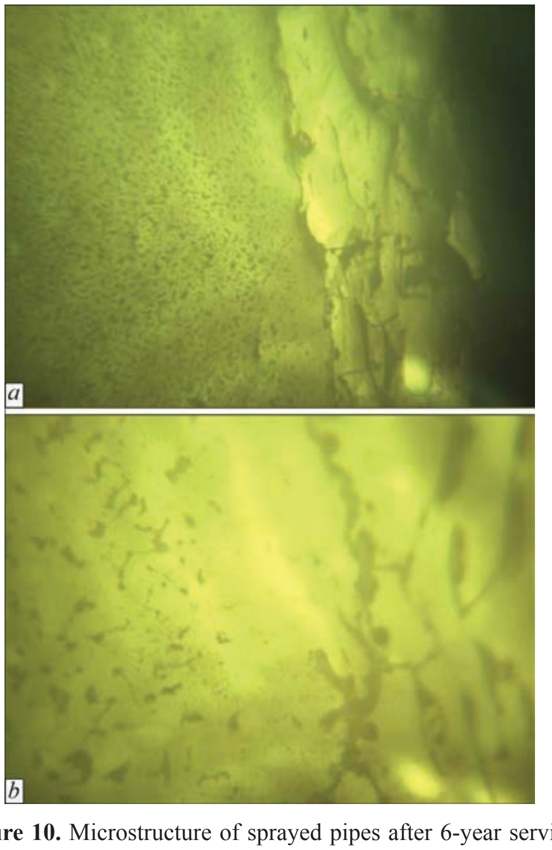

Figure 10. Microstructure of sprayed pipes after 6-year service: *a* — ×100; *b* — ×500

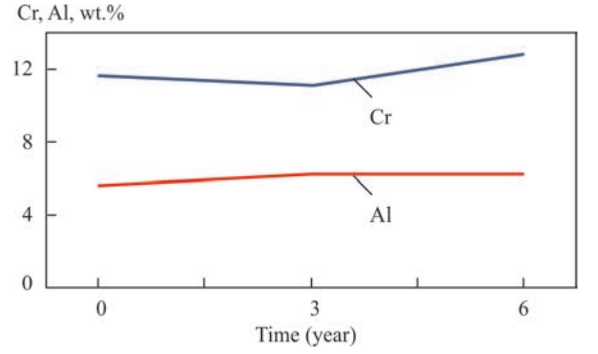

Figure 11. Change in concentration of chromium and aluminium in coating surface layer depending on service life term

Thus, in this case the dependence of hardness effect on the ash wear rate can be assumed and it is possible to conclude that with increase in hardness the wear resistance is growing. This observation is correlated with an erosion wear model [14].

Welding. At Tripolskaya TPP two variants of welding of steel 20 pipes after metallization were investigated. The first one is the electric arc welding of pipes after metallization with electrodes TsU-5 of 2.5 mm with pipes, not subjected to metallization. The second one is the welding with electrodes TsU-5 at abutting of pipes, passed the metallization between themselves.

Welding was carried out in accordance with [15]. Before welding the pipe edges were beveled at 40–45° with their cleaning at edge regions. Diameter of rod of electrodes TsU-5 was 2.5 mm. As to the appearance, the welds were in a good state. Cracking, pores, cavities, undercuts and other external defects were not observed. The surface layer of pipes with metallization in the region of weld joint was cleaned for inspection by nondestructive methods. Ultrasonic testing did not reveal any inner defects in butt joints. Microstructure of metal in a near-weld zone and in the region of welds is good in both cases. The X-ray fluorescent analysis of welded joints revealed the slightly increased chromium content. The increased content of silicon in welded joint is probably connected with an insufficient quality of surface preparation. During

Figure 12. Appearance of pipe after 6-year service (test for convergence of sides)

Table 7. Characteristic of pipes before spraying

Number of unit	Surface from heating side	Surface from working environment side	Material grade	Number of coiled pipe	Number of pipe	Thinning, mm				Operating time
						Left side	Right side	External	Inner	
1	W/E	ASh	Steel 20	152	1	–0.4	–0.4	–0.5	+0.2	11296
1	W/E	ASh	Steel 20	150	1	–0.5	–0.5	–0.8	+0.1	12138
1	W/E (after spraying)	ASh	Steel 20	151	1	+0.4	+0.5	+0.7	+0.2	9084

mechanical tests of welded joint the fracture of specimen occurs in base metal, thus proving the good mechanical properties of weld. Microstructure of metal in near-weld zone and weld zone in both cases are within the standards.

The total sum of financial expenses, paid by the energy-generating enterprise during damage of heating surfaces (failures), which lead to emergency shutdown of power unit, without accounting for lack in profit, is 1011000 UAH. Thus, taking into account the sums of penalties because of failures on the heating surfaces of TPP power units, which can reach several millions of UAH, the implementation of spraying technology has a significant positive effect, because the expenses for implementation of the new technology are 1.5–2.0 times lower as compared with losses, having by TPP during emergency shutdowns. The electric arc spraying will allow extending the service life of the heating surfaces.

Conclusions

In the work the application of method of spraying (metallization) for increasing the operation reliability of TPP power equipment was investigated.

From the data, obtained about mechanical, chemical and structural state of metal of pipe and coating layer, it is possible to make conclusion about the positive experience of implementation of method of electric arc spraying as a promising and high-efficient method of improving the operation reliability of the power equipment.

In spite of a large volume of works, carried out on spraying, there are still problems, which are not completely studied. Among them, the investigation and application of metallization method in the conditions of high-temperature gas corrosion of heating surface of the lower radiation part (LRP), working out of separate instructions and standard documents.

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