Chapter 18
Application of Multicomponent Wear-Resistant Nanostructures Formed by Electrospark Allowing for Protecting Surfaces of Compression Joints Parts

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Abstract The paper discusses the specific features of the process for forming multicomponent wear-resistant nanostructures on the structural steel of 38X2MЮA grade using the method of electrospark alloying (ESA) in the course of simultaneously saturating the surface layers with carbon (carbonizing), sulfur (sulfidizing) and aluminum (aluminizing), which can be used to improve microhardness and wear resistance, prevent frictional seizure, increase resistance to atmospheric corrosion and, thus, protect the surfaces of the parts for compression joints against fretting corrosion. At processing steel using the ESA method by graphite electrode with the discharge energy of Wp = 0.13; 0.52 and 4.9 J and the productivity of 0.5–2.5 cm^2/min, a consistent matter containing sulfur and an aluminum powder is applied to the surface of the part to be strengthened, and then, without waiting for the matter to dry, the alloying process is carried out, while the consistent matter with the content of the aluminum powder of not more than 56% is applied. There were conducted metallographic and durametric analyses of the surface layers of the structural steel after simultaneously aluminizing, sulfidizing, and carbonizing by the ESA method. It was shown that the layer structure consisted of three zones, namely, the white layer, the diffuse zone, and the base metal. While increasing the discharge energy, such surface layer qualitative parameters as thickness, microhardness, and continuity of the white layer as well as surface roughness thereof had been increasing. With increasing the discharge energy,

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the presence of the enhanced sulfur content in the coating had been increasing from 40 to 100 μm.

18.1 Introduction

The most characteristic cases of compression and compression-keyed joints failures are represented by violations of mating strength of their component parts, fretting fatigue damages and breakages caused by fatigue thereof.

Relative micro displacements of connected surfaces observed in the course of wear process occur because of the deformation of parts under loading and vibration conditions accompanying the operation of machines and equipment. The wear intensity increases at operating the parts in aggressive environments. In this case, damaging of the mating surfaces occurs under conditions of fretting corrosion, which, as a rule, takes place with their slight oscillating relative displacements. The significant intensifications of oxidation and frictional seizure are caused by the dynamic nature of loading, when, as at contact, temperature gradient and deformation gradient sharply increase.

Fretting corrosion (FC) is observed at various press fits on rotating shafts, in points of fitting turbine blades, in splined, keyed, bolted and riveted joints. As a result of FC, there is reduced fatigue strength of the parts, which fact can cause serious accidents. The technical result consisting in improving the efficiency of the above said joints, to a great extent, depends on a lot of factors, namely, studying the problems of fretting process, investigating the causes of such a type of wear, analyzing the nature of the processes of interaction and damage of the surfaces of the bodies interacting in a frictional contact, etc. The achievement of this result is one of the most important tasks in ensuring the reliability and durability of machine parts.

18.2 Actual Scientific Researches and Issues Analysis

At the FC, wear occurs at slight oscillatory, cyclic, reciprocating movements with small amplitudes.

The minimum value of the relative micro displacements between the mating surfaces, which is sufficient for fretting occurrence, is extremely small. According to G. Tomlinson, one of the first researchers of the fretting wear phenomenon, its value makes up several nanometers.

It is known that with fretting, quality of a part surface is significantly deteriorated. The roughness parameters are significantly worsened. Under such a condition, there is possible occurrence of deep cavities reaching 200 μm and more deep into the surface layers [1].

Assembling fixed surfaces can be provided, for example, by pressing a shaft into a hole, heating a part having the hole and enveloping it, or by cooling the shaft [2].

For obtaining the teeth of drill bits the method of centrifugal reinforcement with hard alloy is used [3], which provides both increased their wear resistance and the quality of their press joint with the steel body.

The analysis of the results of operating composite mill rolls of a number of unit sizes shows that there are a large number of cases of low reliability of the tire fixation on the roll axis in the course of assembling process by thermal action [4]. This contributed to the development of a wide range of additional structural, technological and other types of fastening methods and means [5].

Damages caused by the FC phenomenon depend on the great majority of factors, namely, relative slip amplitude, contact pressure, a number of cycles, oscillation frequency, material, and environment.

A typical example to study different types of causes for the FC occurrence is an elastic coupling (EC). The main advantage of the couplings with the elastic metal elements, in comparison with gear and bushing-finger couplings, is their high compensating ability, or the ability to operate with offset axes of the shafts without creating significant additional loads on the shafts and their supporting elements (bearings). Low reactive forces have a positive effect on the rotor system, which service life here is less dependent on the accuracy of the shaft alignment. The couplings simultaneously have a torsion stiffness and flexibility in axial and angular directions to compensate for significant shaft decentering values, including misalignment [6].

It should be noted that among all the mating surfaces of the EC parts, a special danger is represented by the mating of 'half-coupling-shaft' type, wherein the outer cylindrical surface of the shaft contacts the inner cylindrical surface of the half-coupling, and the parts here form a preloaded joint [7–10].

Also it should be noted that such critical parts of pump and compressor equipment as half-couplings, which form compression joints with shafts, are commonly made of the heat-resistant and relaxation-resistant structural steel of 38Х2МЮА grade (another designation is a 38ХМЮА grade), which may be replaced by the steels of 38Х2ЮА, 38Х3МВФ, 38ХВФЮ, 38Х2Ю grades.

As a rule, in the course of operation, between the mating cylindrical surfaces, usually in the vicinity of the ends of the half-coupling, there occurs fretting wear (FW), which can lead to loosening fit, increasing vibration resulted in the joint failure and accident. In addition, the FW leads to decreasing fatigue strength of the parts, which event can also cause serious accidents.

To significantly enhance the carrying capacity of compression joints, there has recently been widely developed the scientific and technical direction associated with introducing intermediate layers made of soft and hard materials into the joints contact zones [11–19].

The effectiveness of a particular coating depends on its thickness. There had been carried out the experiments which showed that fretting damage increased when the thickness of the electroplated silver decreased from 125 to 12.5 μm. According to [20], to provide the practical use for the most parts, it has been recommended to apply the coatings in the range of 75–125 μm thick, although in some cases, there were recommended thicknesses up to 300 μm.

In [21], the author cited the results of the work by A. Tuma and F. Wunderlich, wherein, there was discussed a significant effect of increasing the endurance limit of the shafts with the pressed-on parts by carbonizing thereof. It had been found that the endurance limit of the specimens having a diameter of 12 mm with the pressed-in bushings was influenced by their distortions during the process of quenching. After taking action against the distortions, the endurance limit increased from 137.3 to 412.0 MPa. According to the data represented by E. Lehr, the endurance limit of the carbonized specimens having a diameter of 60 mm was more than doubled as in pressure mounting assembly unit.

Today, the chemical and heat treatment (CHT) is one of the most effective methods for strengthening the surfaces of parts to increase their durability. Despite the fact that as a result of the CHT, the quality of the surface layers of machine parts significantly increases, the method has several disadvantages. Those are as follows: a part volumetric heating, resulting in changing its structure and initial geometrical parameters (deformations and warpage); cumbersome and expensive technological equipment; prolonged process duration, use of energy-intensive equipment, etc.

Recently, to improve the quality of the surface layers of machine parts, the method of electrospark alloying (ESA) has become increasingly important, namely, the process of transferring material to the surface of a product by an electric spark discharge [22–24]. Its specific features are environmental safety, locality of action, low energy consumption, firm connection of the applied material with the base, etc. Using different electrode materials, the electroerosion alloying (EEA) method can be used for conducting the processes alternative to the CHT ones, but with significantly lower costs [25–28]. So applying a graphite electrode and saturating the surface of a part with carbon, it is possible to carry out the carbonizing process [29], doing the same with the use of aluminum electrode, to perform the aluminizing process [30], etc.

In [31–35], there are described various sulfidizing processes, which are thermal and chemical ones for treating the products made of iron-based alloys to enrich the surface layers with sulfur. The effect of sulfidizing a part consists of creating a sulfide film on the surface of the part. Sulfides increase the surface activity of metals and alloys, as well as provide wetting the same with surface-active substances and improve the resistance to frictional seizure. The sulfide film, which has a lower strength than the base metal, is easily broken down at friction and separated from the base without plastically deforming it, and with preventing the friction surface from frictional seizure thereof. The iron sulfide (FeS) film increases the wear resistance of friction surfaces and improves their workability. The ferrosulfide coating has a rather high porosity and absorbs a large amount of lubricant with imparting self-lubricating properties to the material.

Chrome coatings, due to their high hardness, wear resistance, and corrosion resistance, are widely used in moving joints (chrome–rubber) of piston pumps and hydraulic drives [36]. However, the low coefficient of friction of chrome coatings paired with steel restrains their use in press joints.

To improve hardness, wear resistance and the atmospheric corrosion resistance of steel parts, an aluminizing method [37] is often used. The method includes applying an aluminum layer on a steel surface (usually by spraying), plastering and annealing. Along with positive results, the above-described technology has several disadvantages. Those are: high cost and laboriousness of the process; the need to be monitored at all stages of the technology; heating the entire part, and accordingly, structural changes in the metal; deformation and warpage; process duration being more than 8 h; high power consumption; negative impact on the environment, etc. Ceramic-aluminum single-layer oxide and two-layer coatings are also used [38–41], which provide comprehensive protection of steel against hydrogen sulfide cracking and wear. A layer of aluminum is applied to the surface of the part and subjected to plasma electrolytic oxidation. This provides an increase in the coefficient of friction and the quality of the fixed connection of parts.

In accordance with [42], the coatings containing intermetallic compounds of the Ti–Al system were created by electrospark deposition of titanium on aluminum and aluminum on titanium. Using the methods of electron microscopy, X-ray diffraction and X-ray microanalysis, the structure, and composition of the coatings have been studied. At forming the electrospark coatings in the air, aluminum oxide and titanium nitride are additionally created. This technology is performed in a protective environment, such as argon, and it is used only for titanium parts. The alloying process of the Ti–Al alloy was also studied in [43]. In [44], there was studied the effect of the compositions of the synthesized Ni–Al alloys on the process for forming the coatings obtained by the ESA method on the stainless steel of 30X13 grade.

According to [1], it is often observed that a soft material as in contact with a harder material (for example, an aluminum alloy with nitrated steel) turns out to be damaged by fretting to a lesser degree than the hard material.

As the results obtained by a lot of researchers have shown, the intensity of fretting development depends on many factors. They include parameters of external mechanical action (contact pressure, amplitude, and frequency of vibrations); the physicochemical and mechanical properties of the surface layers and the nature of their material, the composition and properties of the medium (temperature, humidity, composition) [45–47]. In addition, it is also necessary to conduct studies of the electrochemical properties of materials and coatings for the details of the compounds [48, 49].

The analysis of the references has shown that to protect the surfaces of parts of the compression joints of the ‘hub-shaft’ type from FC, the most promising method might be the ESA method, which allows applying a protective coating in a local place on the surface of one, or if necessary, both of the mating parts. At the same time, there is no need in protecting the remaining parts from the impact of the ESA process. In addition, taking into consideration the positive role of such methods as carbonizing, aluminizing and sulfidizing in protecting the mating surfaces of the parts from the FC, there is occurred a need to solve the problem aimed at creating a new process for forming complex multicomponent C–S–Al coatings for steel parts by the ESA method.

Thus, the aim of the work is to develop a new process for protecting steel parts from the FC with the use of the electrospark alloying method by forming multicomponent

Table 18.1 Dependence of the ESA productivity on the discharge energy

Discharge energy (Wu), J	0.13	0.52	4.6
Productivity, cm^2/min	0.5–0.7	1.0–1.3	2.0–2.5

complex C–S–Al coatings to provide for an increase in the parts wear resistance values, prevent frictional seizure and improve the resistance to atmospheric corrosion.

18.3 Research Methods

To determine the effect of the energy parameters of the ESA equipment on the quality parameters of coatings, there were made specimens of 38Х2МЮА steel grade and with the size of the specimens of 15 × 15 × 8 mm, onto which a consistent matter was applied in the form of a sulfur ointment with 33.3% sulfur content. Before applying, aluminum powder of PAD-0 (ПАД-0 (GOST 5494-95)) grade had been added to the sulfur ointment. The maximum amount of powder was 56%. The further increase in the amount of powder led to decreasing adhesion with the surface to be aluminized. After that, without waiting for the consistent matter to dry out, the process with the use of the EEA method was produced applying the graphite electrode of ЭГ-4 mark at the unit of ≪Элитрох – 52А≫ model using various modes of operation. In that case, the discharge energy values were $W_u = 0.13$; 0.52, and 4.9 j.

Each mode of the ESA method corresponded to its own discharge energy and productivity, that is, the area of the formed coating per unit of time (Table 18.1).

It should be noted that decreasing productivity of the process by the ESA method entails a decrease in the qualitative parameters of the surface layer, that is, the occurrence of burns, and what is most importantly, the destruction of the formed layer, which especially affects when processing on 'rougher' modes with the discharge energy Wu > 1 J. Increasing productivity leads to a decrease in coating continuity.

The metallographic analysis of the coatings was performed using the optical microscope of MIM-7 (МИМ-7) model; the durametric studies were performed on the instrument of PMT-3 (ПМТ-3) model. The surface roughness after processing it by the ESA method was determined using the profilograph-profilometer of 201 model of the "Kalibr" plant production by reading and processing profilograms.

To study the distribution of the elements over the layer depth, a local X-ray microanalysis was performed using the scanning electron microscope of Joel JSM-5400 type equipped with a microanalyzer provided by the ISIS 300 Oxford instruments.

18.4 Research Results

Figure 18.1 shows the microstructure (a) and the distribution of the microhardness for the surface layer (b) made of 38Х2МЮА steel when processing by the ESA

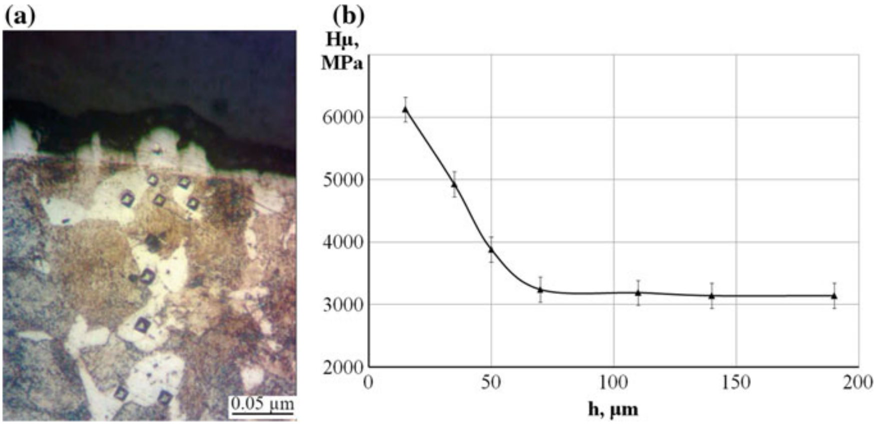

Fig. 18.1 Microstructure **a** and distribution of microhardness **b** for the surface layer of 38X2MIOA steel at the ESA method with Wu = 0.13 J

method with Wu = 0.13 J. The metallographic analysis showed that the obtained layer is not uniform and of low continuity (about 70%). The C–S–Al coating consists of three zones: the white layer of ~10 µm depth, which is not amenable to etching with ordinary reagents, below, there is a transition (diffusion) layer having a depth of ~20 µm, and the base metal, namely, 38X2MIOA steel. At analyzing the microhardness distribution over the depth of the layer, it should be noted that, as a result of electrospark alloying, there is formed a coating characterized by the highest hardness value (up to Hµ = 6100 MPa) for the white layer. As moving away from the surface, the hardness decreases to the hardness of the transition zone (Hµ = 4500–5500 MPa) and the base (Hµ = 3100–3200 MPa).

The results of the micro X-ray spectral analysis (Fig. 18.2) indicate that after processing by the ESA method with Wu = 0.13 J, in the surface layer, there is observed the increased content of carbon, sulfur, and aluminum at a distance of 20, 40 and 35 µm, respectively, and the amount of iron slightly decreases to 25 µm.

At increasing the discharge energy to Wu = 0.52 J, there is the observed formation of a more continuous coating layer (up to 85–90%). Just as with Wu = 0.13 J, the layer consists of 3 zones (Fig. 18.3a). However, with an increase in the discharge energy, the hardness and dimensions of the zones increase (Fig. 18.3). Thus, the hardness of the white layer Hµ ~6600 MPa and its value (h) ~20–30 µm, the transition layer—Hµ = 4500–5000 MPa, h ~20 µm.

Figure 18.4 shows the results of a local micro X-ray spectral analysis of the complex C–S–Al coatings after processing them by the ESA method with Wu = 0.52 J. As it can be seen from the figure, as a result of the ESA, carbon, sulfur, and aluminum diffuse deep into the substrate, namely, 38X2MIOA steel. There is observed an increased content of C, S, and Al, respectively, at a distance of 45, 65 and 57 µm beginning from the surface, with a slight decrease in the iron content (at a distance of ~55 µm).

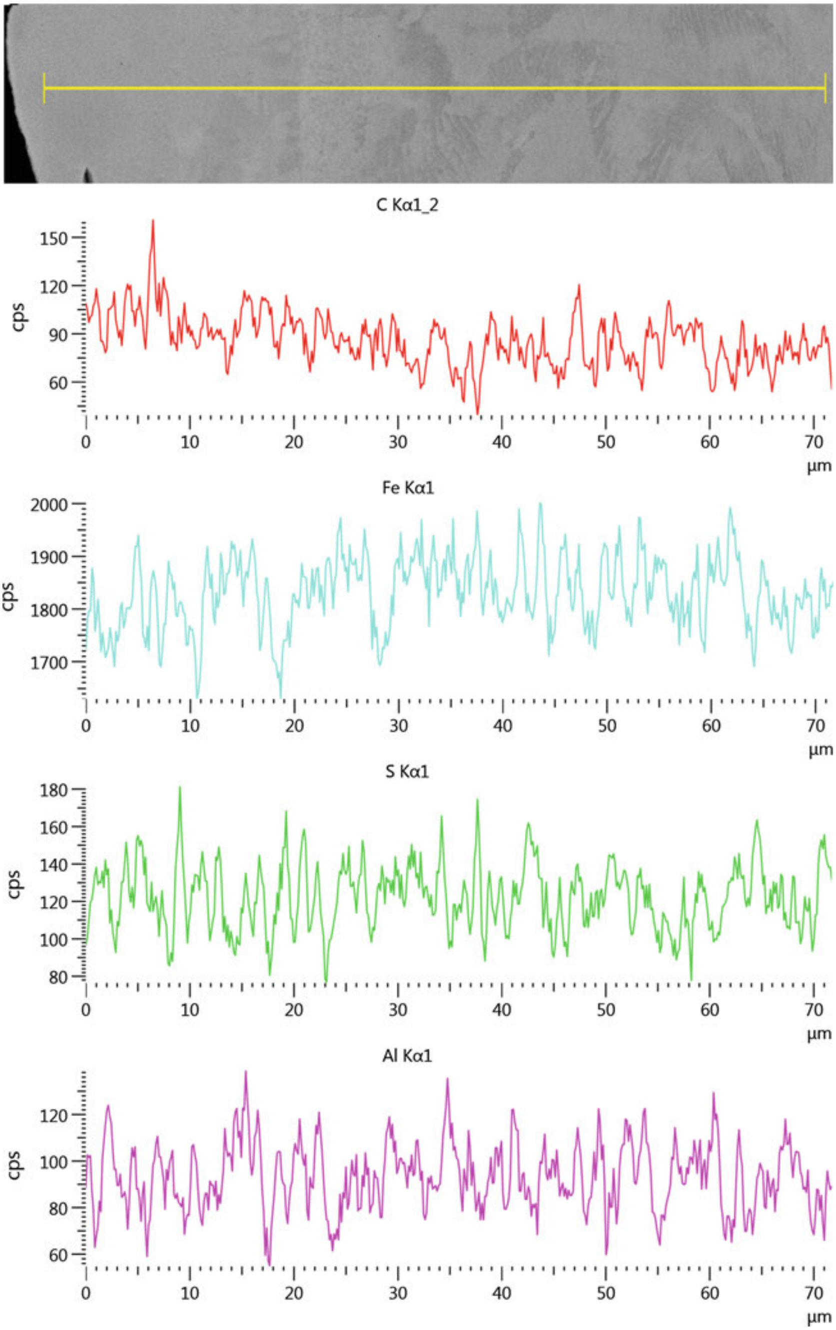

Fig. 18.2 Distribution of elements in the surface layer of 38X2MЮA steel after the ESA method with Wu = 0.13 J

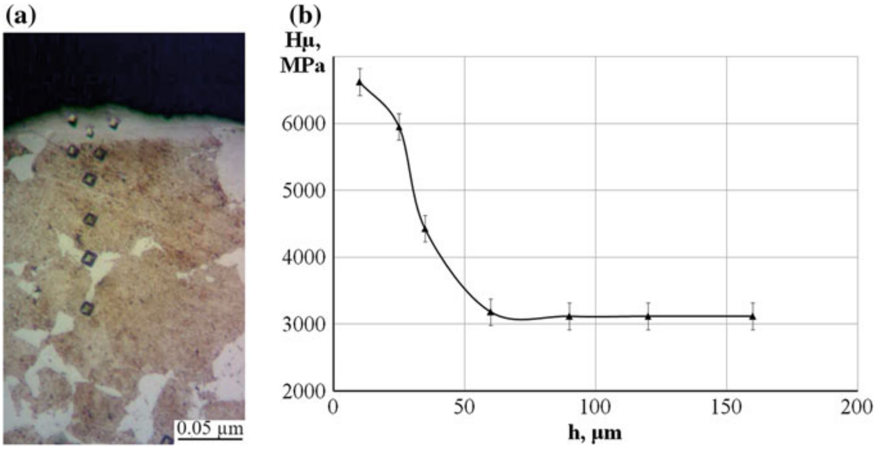

Fig. 18.3 Microstructure **a** and microhardness distribution **b** of 38X2MЮA steel surface layer at processing by the ESA method with Wu = 0.52 J

Figure 18.5 shows the microstructure (a) and the distribution of the microhardness of the surface layer (b) of 38X2MЮA steel at processing the same by the ESA method with Wu = 4.9 J. In this case, the continuity of the layer makes up 100%.

The coating consists of 4 zones. Those are: 1—The sufficiently massive top white layer making up to 50 µm thick and with Hµ ~ 8900 MPa, 2—The light sublayer (20–30 µm) with microhardness of about 6500 MPa, 3—The transition zone of ~20 µm thick, Hµ = 4000–4500 MPa and 4—The base metal of Hµ = 3100–3200 MPa.

Figure 18.6 shows the results of the electron microscopic studies and the local X-ray microanalysis.

On the microstructure obtained with the use of a scanning microscope, there are also observed 4 zones: the surface layer, the sublayer, the transition layer, and the base metal. Studies of the distribution of the elements over the depth of the coating showed that sulfur and carbon are predominantly concentrated on the surface and over the depth up to 100 µm. Aluminum is not evenly distributed in the surface layer, and the greatest amount of its content is observed at a distance of 60–110 µm from the surface, while the iron content herein decreases. It can be assumed that the carbon- and sulfur-containing phases are predominantly formed in the near-surface layers, and the aluminum-containing phases are in the transition zone. Such a distribution of the elements in the coatings obtained by the ESA method seems to be due to the peculiarities of the diffusion processes under the impulse function and the parameters of mutual diffusion of the electrode materials [50].

In Table 18.2, there are shown the qualitative parameters of the complex C–S–Al coatings on the 38X2MЮA steel, obtained by the method of electrospark alloying on various modes.

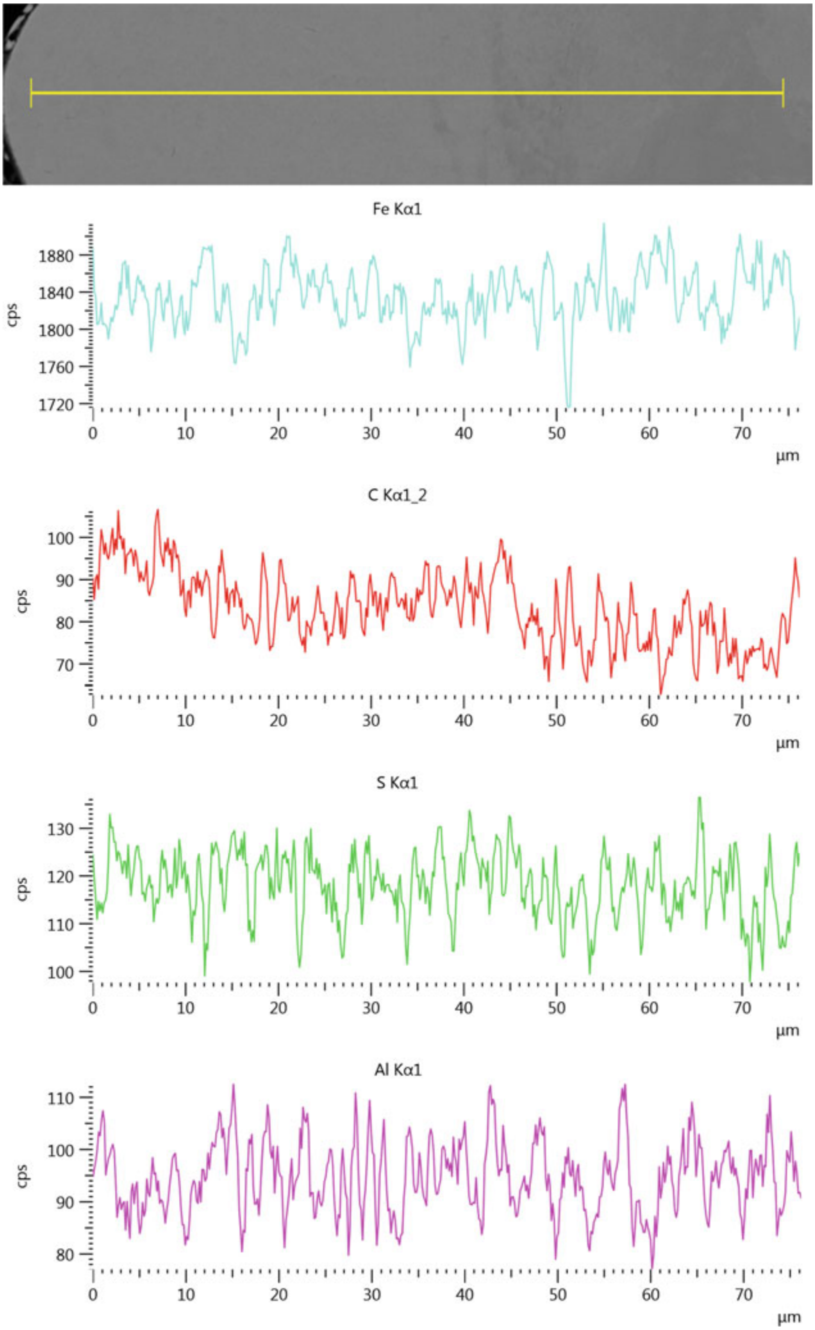

Fig. 18.4 Distribution of elements in the surface layer of 38X2MЮA steel after processing by the ESA method with Wu = 0.52 J

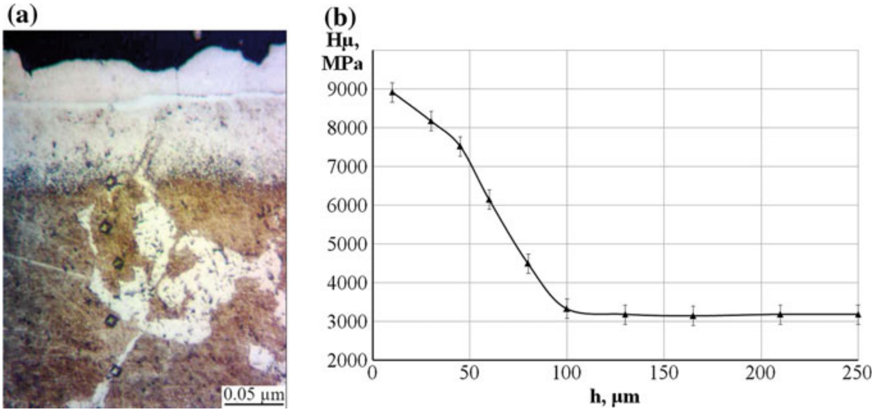

Fig. 18.5 Microstructure (**a**) and microhardness distribution (**b**) of 38X2MЮA steel surface layer at processing the same by the ESA method with Wu = 4.9 J

18.5 Conclusions

A new environmentally-friendly method has been proposed to protect the steel parts mating surfaces of compression joints from fretting corrosion by simultaneously saturating them with carbon, sulfur, and aluminum while processing the same using the method of electrospark alloying.

There have been carried out the metallographic and durametric analyses of the surface layers for the structural steel of 38X2MЮA grade after simultaneously saturating them with carbon, sulfur, and aluminum by the ESA method. It has been shown that the layer structure consists of three zones, namely, the white layer, the diffusion zone, and the base metal. With an increase in the discharge energy from 0.13 to 4.9 J, the thickness, microhardness and continuity of the white layer increase, respectively, from 10 to 50 µm, from 6100 to 8900 MPa and from 70 to 100%, as well as the surface roughness (Ra, Rz and R_{max}) from 1.7; 3.3 and 8.1 to 4.2; 8.7 and 30.2

The presence of sulfur in a consistent matter contributes to the provision of the sulfidizing process. At processing by the ESA method with the discharge energy of 4.9 J, the sulfur content decreases as deepening from the surface, and at the depth of 100 µm, it corresponds to the sulfur amount at the base.

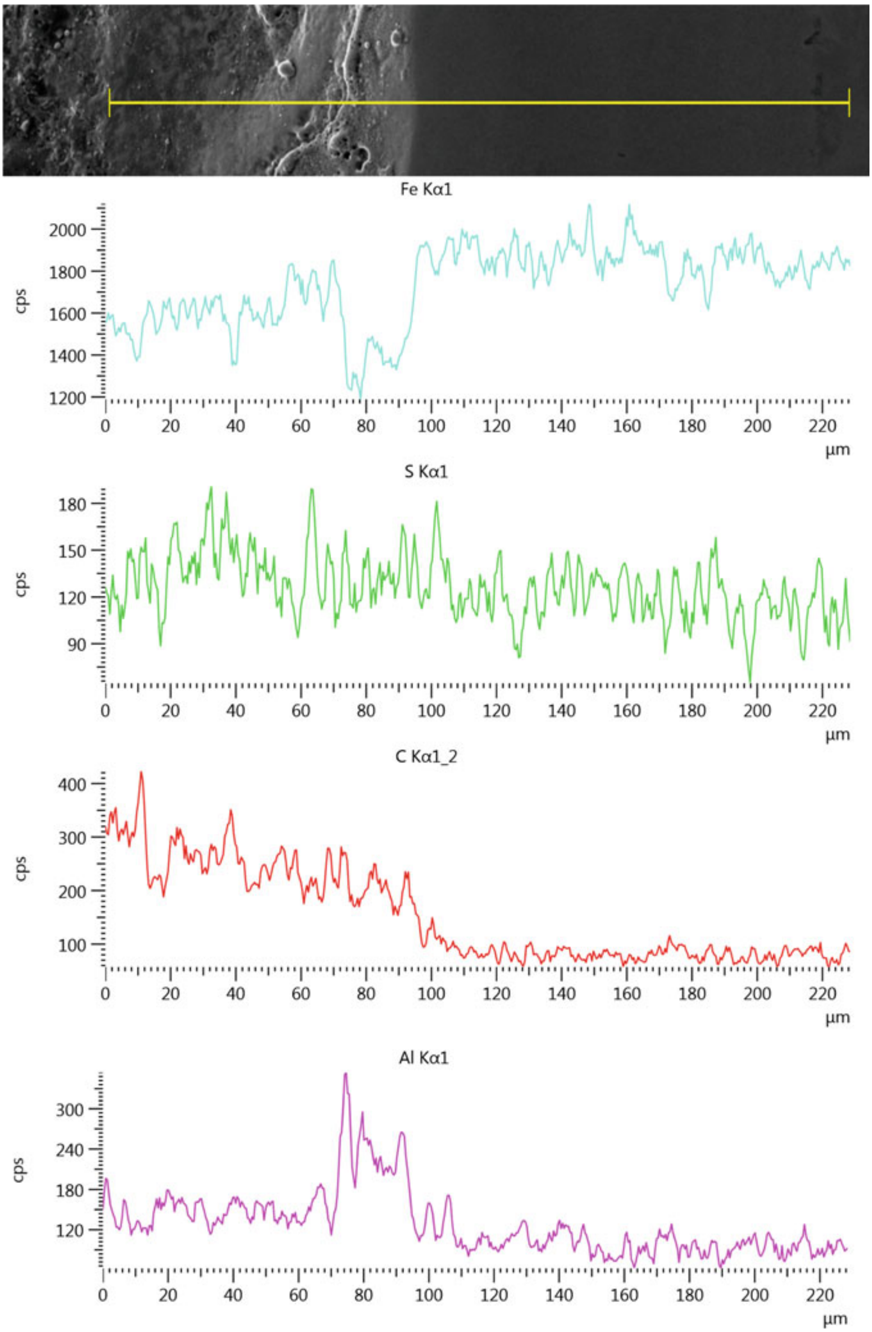

Fig. 18.6 Distribution of elements in the surface layer of 38X2MIOA steel after the ESA method with Wu = 4.9 J

Table 18.2 Qualitative parameters of the complex C–S–Al-coatings on the 38X2MЮA steel after processing by the ESA method

Discharge energy (j)	White layer thickness (μm)	White layer microhardness (MPa)	Roughness (μm)			White layer continuity (%)
			Ra	Rz	R_{max}	
0.13	10	6100 ± 50	1.7	3.3	8.1	70
0.52	30	6600 ± 50	2.3	3.9	9.1	90
4.9	50	8900 ± 50	4.2	8.7	30.2	100

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