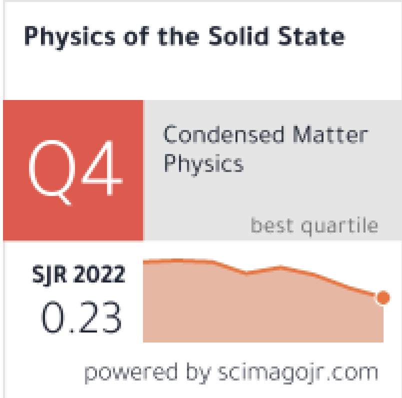

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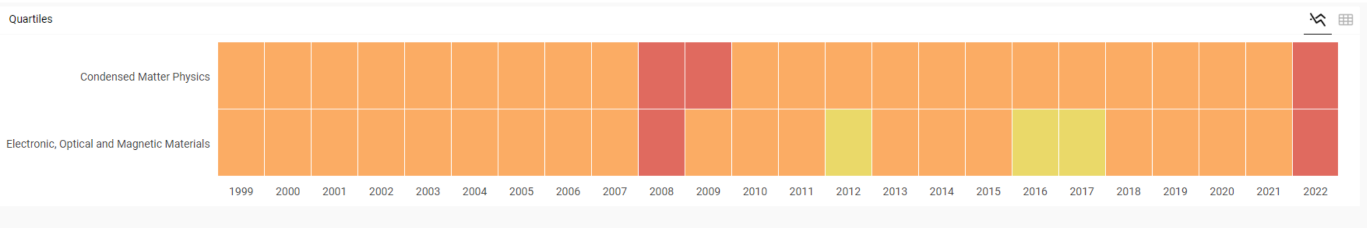

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Structural–Phase State of a Surface of Electron-Beam Treatment of a Steel Subjected to Electroexplosive Aluminizing

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Abstract—Steel 45 surface is aluminized by electroexplosive alloying. The aluminized surface is treated by an electron beam. The structure and mechanical properties of the surface layer are studied. The electroexplosive is shown to lead to the formation of a high-porous coating on the steel surface. The subsequent electron-beam treatment in a mode of melting the surface layer is accompanied by the formation of a smooth surface, the increase in the microhardness in a layer thickness of 45–50 μm by a factor of 3.5 as compared to that of the initial material. The physical nature of the increase in the strength properties of a steel surface layer is explained.

Keywords: electroexplosive aluminizing, electron-beam treatment, structure and properties of modified layer

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INTRODUCTION

One of promising methods of processing surfaces of metals and alloys is the method of electroexplosive alloying (EEA) in which pulsed plasma jets formed when discharging capacitive energy storages through conductors. The working substance of a plasma accelerator is used not only for heating surface layers of materials but also for their alloying [1, 2]. The facts presented in [3, 4] indicate multiple increase in the microhardness, wear-resistance and high-temperature strength, and several other operating properties of a wide nomenclature of parts of machines, structures, and instruments subjected to EEA. As a jet is formed, its front forms a plasma component, but condensed particles are arranged in the rear of the jets due to their high inertia. This fact leads not only to surface alloying, but also to the formation of coatings that are, as a rule, high-porous and contain a great number of a drop fraction, microcraters, and microcracks, which limits, in some cases, possibilities of applying the method in practice. As a rule, such a coating is removed by mechanical treatment of the part, which leads to the loss of alloying elements and, correspondingly, to a rise in the price of the EEA process. In this work, we increase the quality of a hardened surface by its complex treatment. To do this, the electroexplosive treatment surface was additionally irradiated by submillisecond electron beams in the multipulsed mode. The aim of this work is to analyze the evolution of the structure and mechanical properties and to reveal the mechanisms of hardening the surface layer of the carbon steel after complex treatment.

1. EXPERIMENTAL

Steel 45 with a ferrite–pearlite structure was used as a substrate material. EEA was carried out by electrical explosion of a 20-μm-thick aluminum foil. The conditions of pulsed liquid-phase alloying were given by the value of the charge voltage of the accelerator energy storage, the nozzle channel diameter, and the distance from its cut to the sample, which were 2.3 kV, 20 mm, and 20 mm. In this case, the depth and the radius of the alloying zone were maximal [4]. The EEA time was 100 μs, the power density absorbed at the jet axis was 4.5 GW/m^2, and the pressure in the shock-compressed layer near the surface 11.2 MPa. The action zone thickness in its central region was 25 μm [4]. The electron-beam treatment of the alloying surface was carried out on a Solo laboratory installation [5]. The electron-beam energy density was 0.2 MJ/m^2, the pulse duration 50 μs, pulse repetition rate, 0.3 Hz; the number of pulses 2–200. The treatment was performed in an inert argon medium in the working chamber at a pressure of ~2.5×10^{-4} Torr. The studies of the structures of the irradiation surface, the brittle fraction surface, the surface of an etched "skew" metallographic section with an angle of incli-

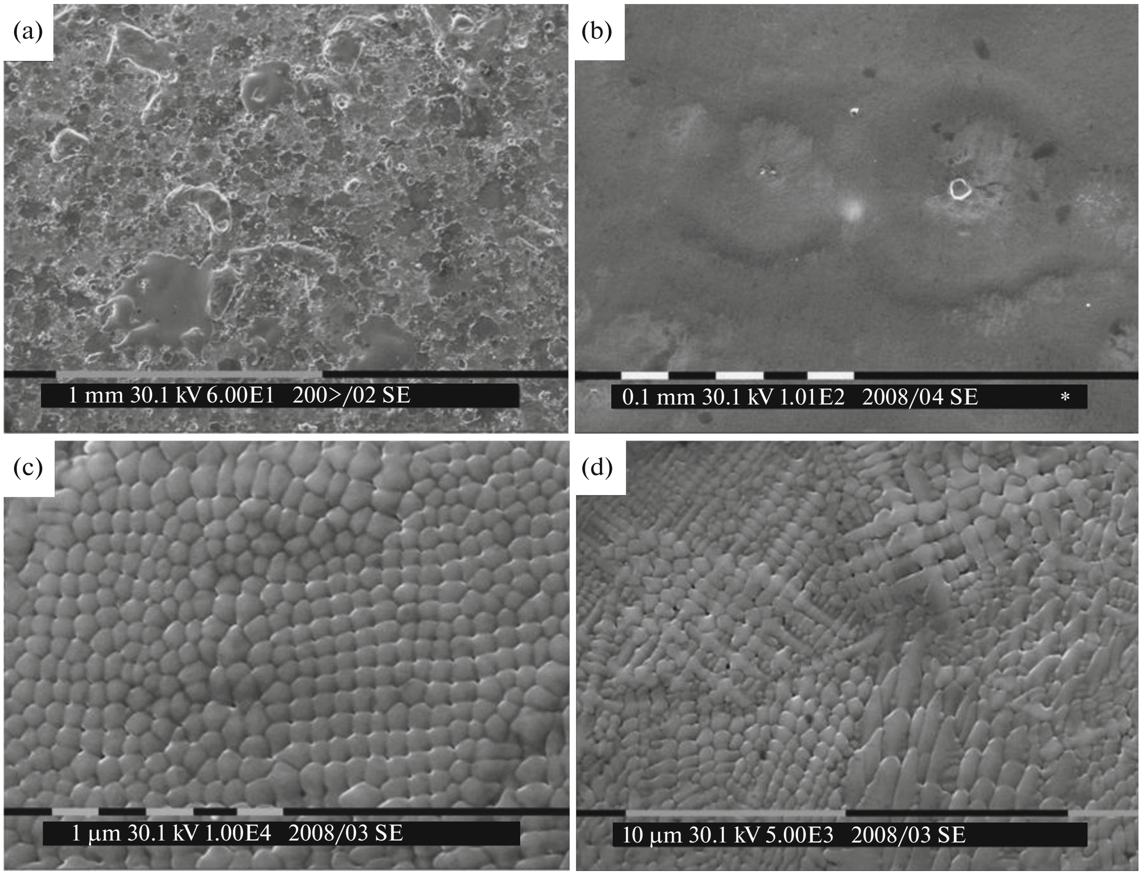

Fig.1. SEM images of the steel 45 surface after (a) subsequent electron-beam treatment (20 J/cm^2, 50 μs, 0.3 Hz) at (b, c) 10 and (d) 200 electron-beam pulses.

nation of 6°–7° of the modified samples were carried out by optical microscopy, SEM, TEM. and electron diffraction methods. The distribution of aluminum over the sample thickness was analyzed using an EDAX ECON IV microanalyzer mounted on a Philipd SEM 515 scanning electron microscope having a limiting accuracy of determining concentration of 5% and spatial resolution of the microanalysis 1.0, 1.0, 3.0–5.0 μm. The changes in the mechanical properties of the material were characterized by the microhardness determined by the Vickers method at a load of 0.98 N by averaging of 80–100 indentations per one point (the measurement accuracy was 7%).

2. RESULTS AND DISCUSSION

The complex treatment leads to the melting of a surface layer and liquid-phase mixing of elements of coating and substrate. In the case of the optimum mode of operating the electron source [6], a smooth surface with the minimum number of microcraters and microcracks is formed (Fig. 1). The material cooling is accompanied by the dendrite crystallization in which the morphology and the average sizes of elements are determined by the mode of electron-beam treatment (Figs. 1c, 1d).

As a result, a multilayer structure forms in the steel [6]. The SEM microscopy of an etched metallographic section revealed the melt solidification zones as the weakly etching surface layer (layer I), the intermediate layer (layer II), and the heat affected zone (layer III) which smoothly change one to another. In this case, the complex treatment leads to substantial (by a factor of ~2) decrease in the surface weakly etched layer (layer I) thickness in some places, but in other places, to the same increase.

EEA is accompanied by the saturation of the surface steel layer with aluminum: at the depth of ~3 μm, the aluminum concentration is ~8 wt % and quickly decreases with the distance from the alloying surface. Subsequent electron-beam treatment (20 J/cm^2, 50 μs, 0.3 Hz, 10 pulses) leads to a decrease in the aluminum concentration in a surface layer of the sample to ~4.5 wt % and fast decrease as the distance from the treated surface increases.

EEA of the steel with aluminum is accompanied by an increase in the hardness of the surface layer of the sample by a factor of ~4 (Table 1). As the distance

Table 1. Microhardness of the surface layer of the steel subjected to EEA and subsequent electron beam treatment (20 J/cm^2, 50 μs, 0.3 Hz)

Type of treatment	N, pulses	H_V, MPa
EEA	1	825
EEA + electron-beam treatment (complex treatment)	10	810
	50	370
	100	550
	200	258

from the treated surface increases, the microhardness decreases and becomes equal to the microhardness of the initial state at the depth 20–25 μm. The complex treatment of the steel surface by the optimum mode of electron-beam action (20 J/cm^2, 50 μs, 0.3 Hz, 10 pulses) leads to insignificant decrease in the microhardness of the surface layer as compared to that of the steel surface layer after EEA (Table 1). Simultaneously with this, the complex treatment in the places, where the layer I thickness increased, is accompanied by substantial increase in the microhardness: it is higher by a factor of 3.8 as compared to the microhardness of the initial steel, and the depth of hardening reaches 40–45 μm.

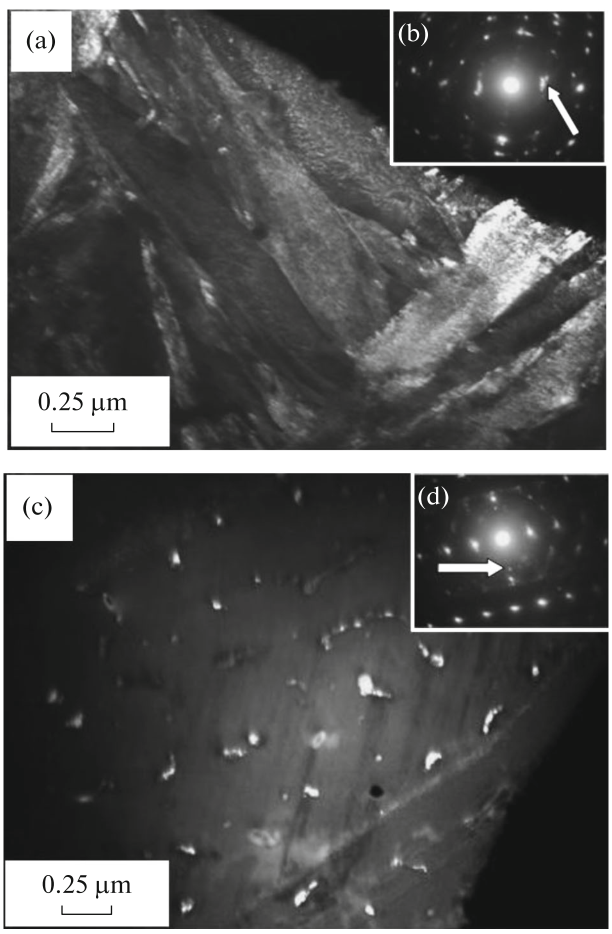

Fig. 2. Electron-microscopy image of the structure of a surface layer of steel 45 subjected to the complex treatment (N = 10 pulses): (a, c) dark fields obtained in reflections (a) [110]α-Fe + [002]γ-Fe and (c) [002]Al_5Fe_2; (b, d) microelectronograms (the arrows indicate the reflections in which dark fields are obtained).

The layer-by-layer electron-microscopy microdiffraction analysis of the structure and the phase composition of the steel subjected to the complex treatment (we studied the layer immediately adjacent to the treating surface) allowed as o reveal the reasons of nonlinear change in the microhardness of the surface steel layer when increasing the number of electron-beam pulses. Our studies showed that a rapid-quenching structure forms in the sample surface layer after 10 electron-beam pulses. This structure consists of crystals of packet and lamellar martensites, interlayers and islands of retained austenite, and Al_5Fe_2 iron aluminide particles (Fig. 2).

After 50 electron-beam pulses, a grained–subgrained structure forms in the surface layer. Interlayers of the γ phase (retained austenite) and iron aluminide Al_5Fe_2 particles are arranged along α-phase grains (Fig. 3).

After 100 electron-beam pulses, a polybase structure forms in a surface layer of the steel: first, quenching-type structure: lamellar (mainly) and packet martensite (Fig. 4a), retained austenite (interlayers, islands, and grains); second, ferrite grains; third, "pseudo-pearlite" grains (Fig. 4b). Particles of iron aluminides Al_5Fe_2 and Fe_3Al are arranged along grains and subgrains.

After 200 electron-beam pulses, we observe in the surface steel layer the structure formed as a result of rapid quenching and subsequent tempering under action of a residual heat, namely, the grain–subgrain structure based on α iron and "pseudo-pearlite" grains (Fig. 5a). There are numerous precipitates of aluminides ($Al_{13}Fe_4$; Al_5Fe_2; Al_2Fe; $AlFe_3$) and iron carbide along grain and subgrain boundaries and also in the bulk (Fig. 5).

The studies of the structure, the elemental and phase compositions and mechanical properties of the surface layer of steel 45 subjected to the electroexplosive aluminizing and subsequent electron-beam treatment show that the increase in the material strength has a multifactor character. This fact ids due to: first, the formation of the martensitic structure; second, the decrease in the average grain size; third, the precipitation of nanosized iron aluminide particles; fourth, an increase in the scalar density of ferrite grain dislocations and ferrite interlayers of pearlite grains; fifth, the fragmentation of ferrite grains and the formation of subgrains; and, at last, sixth, the formation of solid solution of aluminum and carbon in α iron.

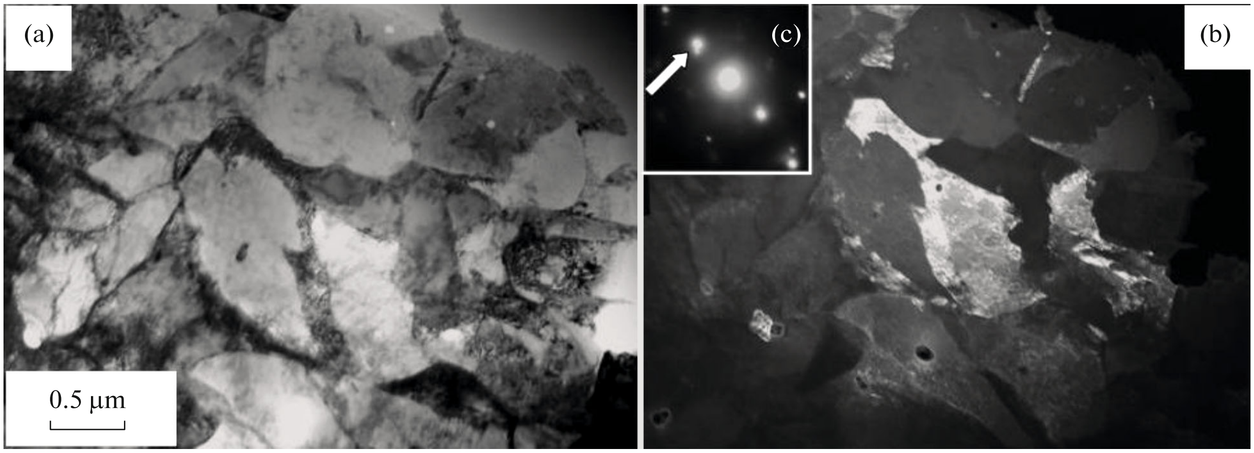

Fig. 3. Electron-microscopy image of the structure of a surface layer of steel 45 subjected to the complex treatment ($N = 50$ pulses): (a) bright field, (b) dark field obtained in reflection [110]α-Fe + [002]γ-Fe; (c) microelectronogram (the arrow indicates the reflection in which dark field is obtained).

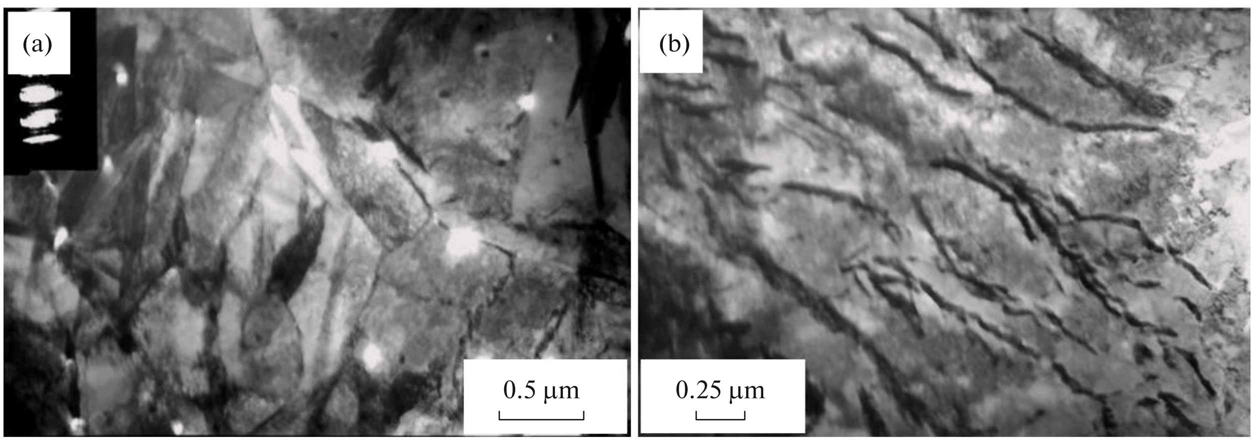

Fig. 4. Electron-microscopy image of the structure of a surface layer of steel 45 subjected to the complex treatment (N = 100 pulses): (a) pseudo-pearlite grains, (b) ferritic–austenitic grain–subgrain structure.

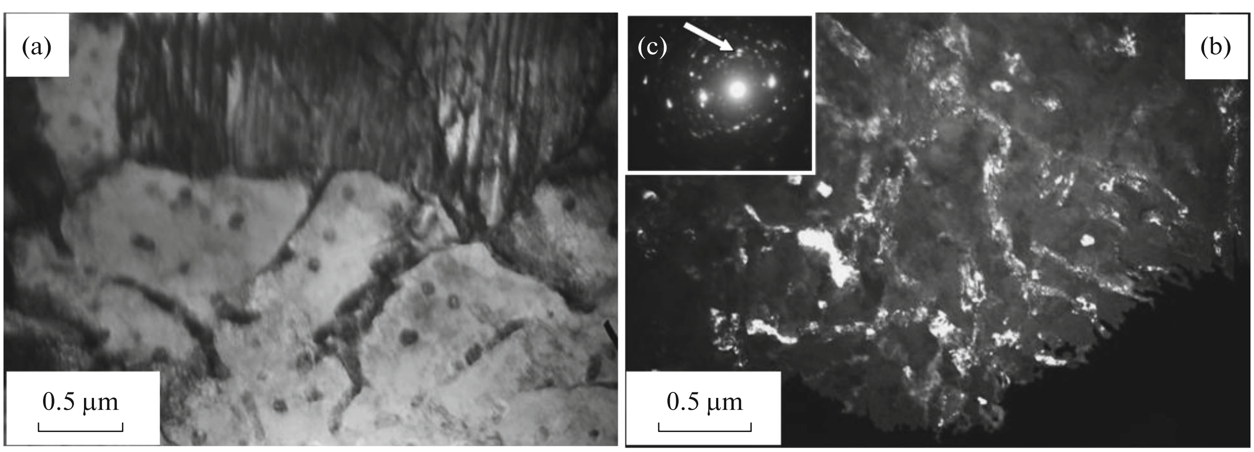

Fig. 5. Electron-microscopy image of the structure of a surface layer of steel 45 subjected to the complex treatment (N = 200 pulses): (a) bright field, (b) dark field obtained in the [001]Al_5Fe_2 reflection, (c) microelectronogram (the arrow indicates the reflection in which dark field is obtained).

CONCLUSIONS

Electroexplosive aluminizing is accompanied by the saturation of the steel with aluminum and the formation of the surface layer, the microhardness of which is substantially (by a factor of ~4) higher than that of the sample core. The subsequent electron-beam treatment in the optimum irradiation mode leads to a substantial increase in the thickness of the hardened layer (to 40–45 μm) at insignificant decrease in its microhardness. The increase in the strength characteristics of the surface layer of the steel subjected to the complex treatment is due to the formation of the rapidly quenched structure and the precipitation of iron aluminides.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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