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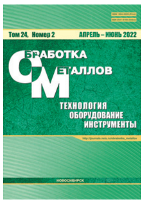

Influence of boriding and aluminizing processes on the structure and properties of low-carbon steels

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ABSTRACT

Introduction. Boriding and aluminizing are among the effective methods for improving the performance properties (corrosion resistance, heat resistance and wear resistance) of machine parts and tools. Solid-phase methods of carrying out techniques of thermochemical treatment (*TCT*) require long-term exposure at elevated temperatures, which negatively affects the structure and properties of the base material. From these positions, the selection of reasonable temperature-time parameters of solid-phase boriding and aluminizing processes is an urgent task. **The purpose of this work** is to assess the effect of low-temperature boriding and aluminizing processes on the structure and microhardness of diffusion layers on the surface of low-carbon steels. The paper considers two grades of steels with a carbon content of up to 0.4 %: low-carbon steel *St3* and alloy steel *3Cr2W8V*. The use of the second steel is due to the need to identify the effect of alloying elements in steel on the thickness of diffusion layers and its composition. Powder mixtures based on boron carbide and aluminum carbide are selected as sources of boron and aluminum. **Results and discussions.** It is found at a process temperature of 900 °C and holding for 2 hours after boriding, iron borides are formed on the surface of both steels. At the same time, two borides FeB and Fe_2B are detected on *St3* steel by X-ray phase analysis (*XRD*), and only the Fe_2B phase is detected on *3Cr2W8V* steel. After aluminizing, aluminum-containing phases such as Al_5Fe_2, Na_3AlF_6 and Al_2O_3 are formed in both steels. The thickness of the resulting diffusion layer on St3 after boriding is 35 µm, after aluminizing – 65 µm. The thickness of the diffusion layer on *3Cr2W8V* steel is equal to 15 µm after boriding and 50 µm after aluminizing, which is significantly less than on carbon steel and is obviously due to the effect of alloying elements. It is established that TCT leads to a significant increase in the microhardness of the samples surface. Thus, the maximum microhardness of *St3* steel increased to 2,000 HV, and the maximum microhardness of *3Cr2W8V* steel increased to 1,700 HV after boriding. The microhardness after aluminizing is comparable for both steels and is equal to 1,000–1,100 HV. Elemental analysis of the upper sections of the diffusion layers shows that the content of boron (7–9 %) and aluminum (50–53 %) corresponds to the detected *XRD* iron borides and aluminides. In all cases, there is a gradual decrease in the diffusing elements in the direction from the surface to the base.

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Introduction

An important goal of modern materials science is to increase the strength and wear resistance of tools and various machine parts by means of diffusion saturation of the metals and alloys with various chemical elements. It is hard to achieve the specified mechanical and operational properties using common heat treatment (quenching and tempering). A better alternative is thermochemical treatment (*TCT*), when various chemical elements diffuse into the surface of metals and alloys. Metal working parts, subjected to *TCT*, can replace products made of expensive special steels and alloys [1-2].

Currently, there are several methods of *TCT*, depending on the saturating medium: gas, liquid and solid-phase (in powders and pastes) [3-4].

It is known that borited layers have high hardness, corrosion and wear resistance. Saturating mixtures based on boron carbide are widely used for boriding in powder mixtures and pastes [5]. Aluminizing is the process of surface saturating with aluminum to improve oxidation resistance at high temperatures and atmospheric corrosion resistance. Various mixtures based on the powders of aluminum or ferroaluminum, aluminum oxide, etc. are used for aluminizing [6, 7].

It should be noted that the solid-phase *TCT* methods require long-term exposure at elevated temperatures, which adversely affects the structure and properties of the base metal.

There are other methods for improving the surface properties of machine parts that do not require long-term exposure at elevated temperatures, such as concentrated energy streams (*CES*). Laser and electron beam treatment (*EBT*) are capable to heat a material's surface rapidly and avoid the mentioned drawback [8-10]. There are also methods of the combined treatment, where common *TCT* is followed by subsequent laser treatments and *EBT* [11-13]. The latter method allows modifying the previously obtained diffusion layer and eliminating its defects (layering and phase inhomogeneity along the layer depth, brittleness, high surface roughness).

It should be noted that the *CES* methods require costly equipment. Its use is justified when the necessary properties cannot be attained through common surface techniques. Thus, it is reasonable to carry out a combined treatment with the *TCT* as a first stage of the treatment to obtain a continuous protective layer over the entire surface area. Next, the most critical areas are additionally subjected to *EBT* to modify the obtained diffusion layers. Another opportunity is to carry out electron beam alloying (*EBA*) as a second treatment. For example, first, powder aluminizing with furnace heating is carried out, followed by the *EBA* with boron carbide, or in reverse mode, i.e., common powder pack boriding followed by the *EBA* with aluminum. It is known, that the combined process of saturation with boron and aluminum (boroaluminizing) makes it possible to synthesize multifunctional layers [14, 15].

This paper contains the materials on the first stage of treatment as independent processes that improve the set of physical and mechanical properties of steels over the entire surface area of a product.

The purpose of this work is to determine the impact of boriding and aluminizing on the structure and properties of the diffusion layer on the surface of low-carbon steels. The paper presents the test results of the low-temperature modes of *TCT*. A comparative analysis of the structure and properties was carried out via examples of two steel grades.

Methodology

The following powders were used for saturating: boron carbide B_4C of *F-220* grade, aluminum powder *PA-4* grade (6058-73 State Standard), aluminum oxide Al_2O_3 analytical pure class (8136-85 State Standard) and sodium fluoride *NaF* analytical pure class (4463-76 State Standard).

A mixture of 96% B_4C + 4% *NaF* was used for the boriding process. The aluminizing mixture consisted of 48% *Al* + 48% Al_2O_3 + 4% *NaF*.

The *TCT* in powders were carried out in the *PM-16P-TD* laboratory furnace at a temperature of 900 °C. The samples of *St3* steel and *3Cr2W8V* die steel with the size of 20×20×10 mm were subjected to *TCT*. The duration of the treatment process was 2 hours. As it is known, *St3* steel is used for the bearing elements of welded and non-welded structures and parts (composition, in wt. %): *Fe* ≈ 97, *C* 0.14-0.22, *Si* 0.15-0.3, *Mn* 0.4-0.65). *3Cr2W8V* steel is used for a heavily loaded press tool utilized for hot deformation of alloyed structural steels and heat-resistant alloys (composition, in wt. %): *Fe* ≈ 87, *C* 0.3-0.4, *Si* 0.15-0.4, *Mn* 0, 15-0.4, *Cr* 2.2-2.7, *W* 7.5-8.5, *V* 0.2-0.5, *Mo* up to 0.5). The powder mixture was poured into the crucible along with the test samples; then the crucible was packed and sealed with a fusible seal from the top. The crucibles were cooled in the open air at room temperature. At the end, the crucibles were unpacked and the samples were cleaned from the remnants of the saturating mixture.

The composition and structure of the diffusion layer were determined on a *JSM-6510LV JEOL* (Japan) scanning electron microscope with an *INCA Energy 350 Oxford Instruments* (Great Britain) microanalysis system at the Progress Science Center, East Siberia State University of Technology and Management.

The phase composition on the samples' surfaces was determined by a *D8 ADVANCE Bruker AXS* X-ray diffractometer in copper radiation with a shooting interval of 10-70° at the Science Center of the BIP SB RAS.

The microhardness test of the obtained layers was carried out by a *PMT-3M* microhardness tester. The load was 50 g. The *Nexsys ImageExpert MicroHardness 2* software package (9450-76 State Standard) was used to calculate the microhardness values. Microstructures were photographed by a *METAM RV-34* metallographic microscope with an *Altami Studio* digital camera (Russia). The *Nexsys ImageExpert Pro 3.0* software package was used to determine the thickness of the diffusion layer.

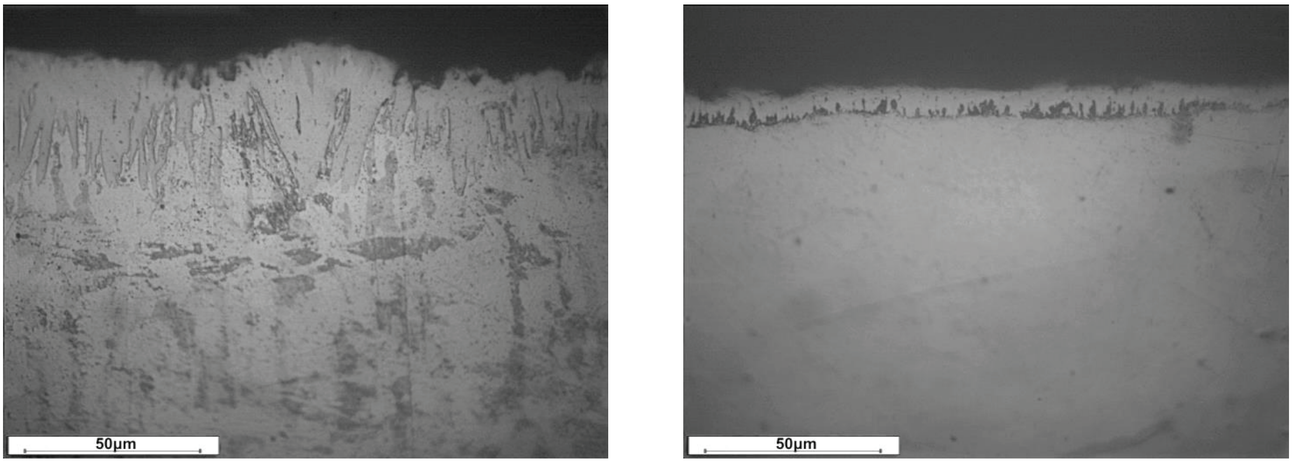
Results and discussions

The boriding and aluminizing processes were carried out on *St3* and *3Cr2W8V* steel samples at a temperature of 900 °C for 2 hours.

Figures 1 and 2 show microphotographs of the steels structures after *TCT*.

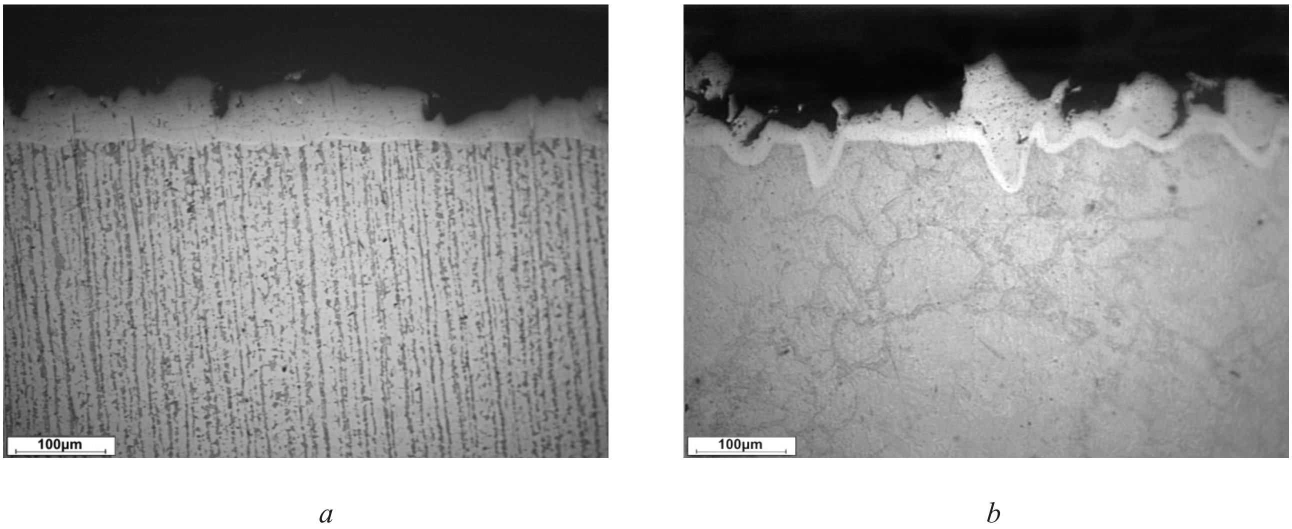
These figures clearly show the acicular structure of the borided layers. The thickness of the resulting diffusion layer on *St3* steel was 35 µm, and on the alloyed steel it was 15 µm. It is known that boriding of low-carbon steel under the same time-temperature modes in metal-oxide-containing mixtures (based on boron and aluminum oxides) provides a layer thickness of 50 µm [16]. A considerably thinner layer was formed on *3Cr2W8V* steel compared to the low-carbon steel. This was due to the high concentration of alloying elements, which hindered the diffusion of boron. The resulting layer thickness was consistent with the borated layers obtained by the liquid method and in pastes of various compositions [16].

Figures 2, *a* and 2, *b* show the structures of the studied steels after aluminizing. A more even surface layer was formed on *St3* steel, consisting mainly of Al_5Fe_2. At the boundary with the base metal, *AlFe*, $AlFe_3$ phases and a solid solution in *α-Fe* were gradually formed [17–19]. The thickness of the diffusion



a *b*

Fig. 1. Microstructures of *St3* (a) and *3Cr2W8V* (b) steels after boriding



a *b*

Fig. 2. Microstructures of St3 (a) and *3Cr2W8V* (b) steels after aluminizing

layer on *St3* steel was 65 μm, which was comparable to the layers obtained by spray aluminizing and in molten salts (galvanic method) [17].

A layer with an average thickness of 50 μm and an uneven interface with the base metal were visible on the sample of *3Cr2W8V* steel after aluminizing. Local extrema of the layer thickness, apparently, were the places of the steel surface melting and partial transition to the liquid state in these areas. This was also accompanied by increased diffusion in proportion to the increase in temperature. The latter was obviously caused by the passage of an exothermic metal reduction reaction. At the same time, the layer phase composition was similar to the composition on *St3* carbon steel, where iron aluminides were additionally alloyed with *Cr*, *W*, and *V*.

The low quality of the surface after aluminizing was due to the high reactivity of aluminum, accompanied by interaction with oxygen and other elements of atmospheric air [20].

Figure 3 shows the microhardness distribution over the distance after the boriding process of the both steels.

The maximum microhardness on *St3* steel was observed on the layer at a distance up to 10–15 μm from the surface and reached 1,919.6 HV, which is typical for boriding due to the formation of solid iron borides. The maximum value of 1,684.8 HV was observed at a distance of 15 μm from the surface on *3Cr2W8V* steel, probably in the zone with the highest concentration of borides.

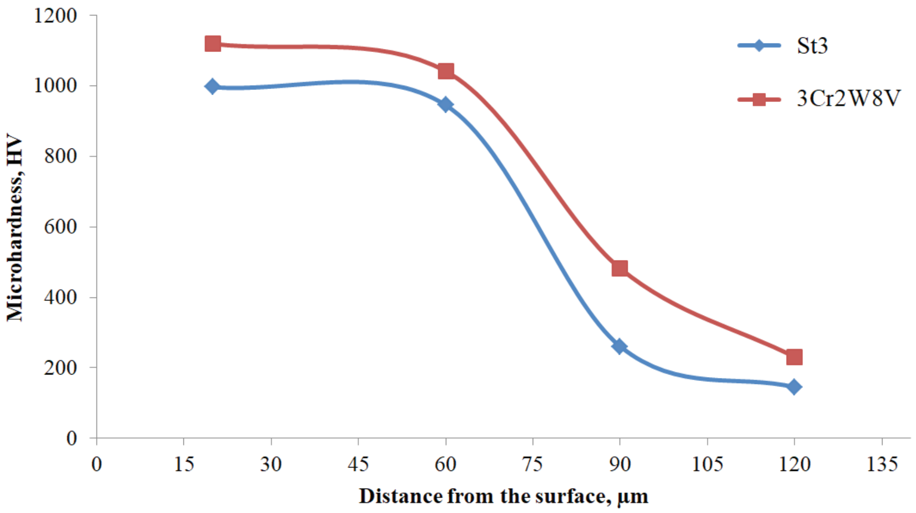


Fig. 3. Microhardness distribution over the layer depth on steels after boriding

Figure 4 shows the microhardness distribution over the distance after the aluminizing process of the both steels.

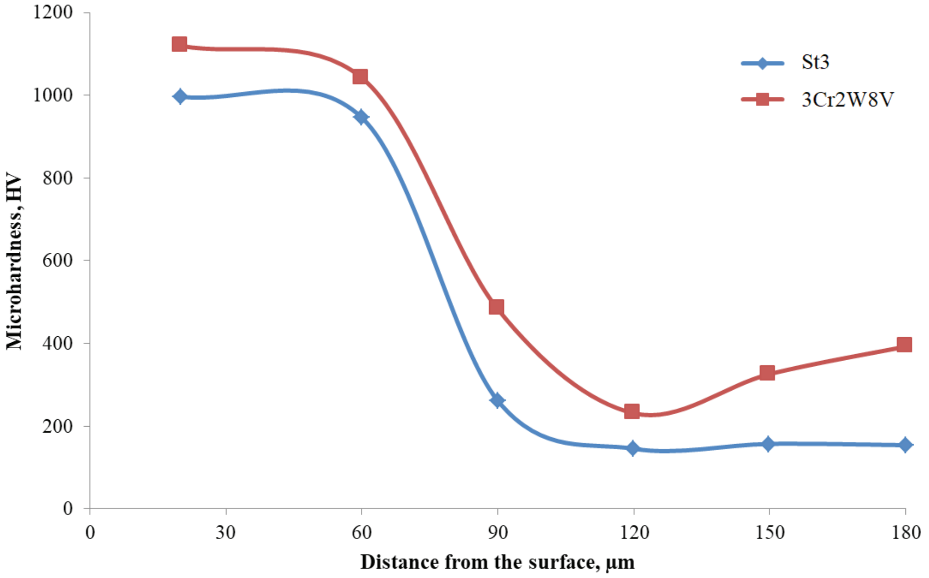
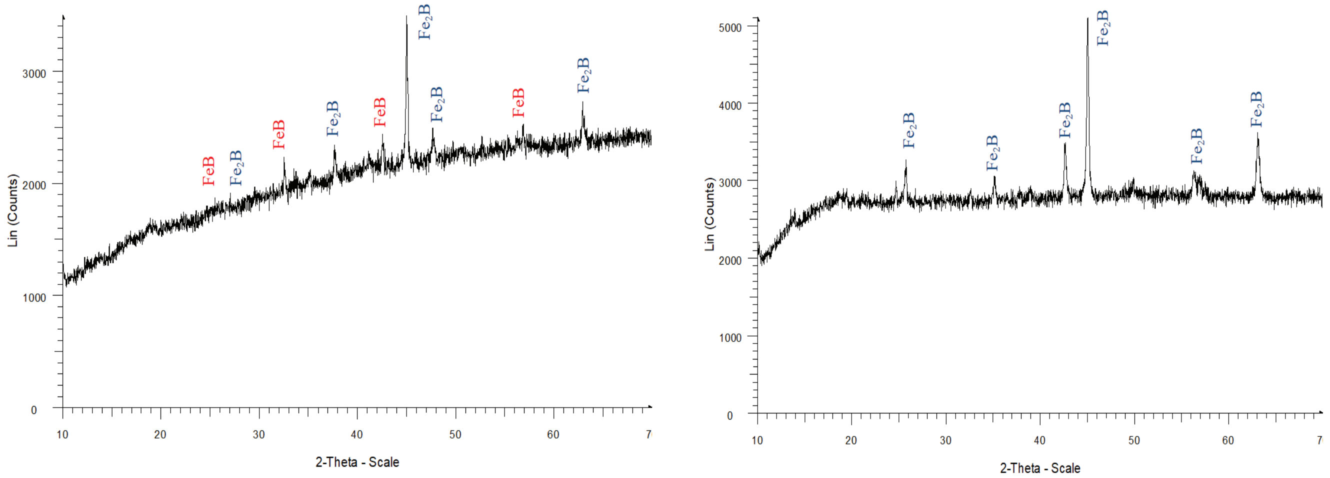


Fig. 4. Microhardness distribution over the layer depth on the steels after aluminizing

The microhardness distribution curves obtained after the aluminizing process on *3Cr2W8V* steel were the most promising. The maximum value of microhardness for *St3* steel was 996 HV, and for *3Cr2W8V* steel it reached rather a high value of 1,119 HV. An indicative increase in microhardness at a distance of 150–180 µm from the surface was visible for the alloy steel. This local increase in microhardness corresponded to the transition zone directly under the layer, which supposedly indicated an increased content of chromium and tungsten carbides. Its concentration increased due to the displacement by aluminum diffusing from the surface. The substitution of the carbides deep into the base metal presumably occurred because of its mutual insolubility with aluminides [21].

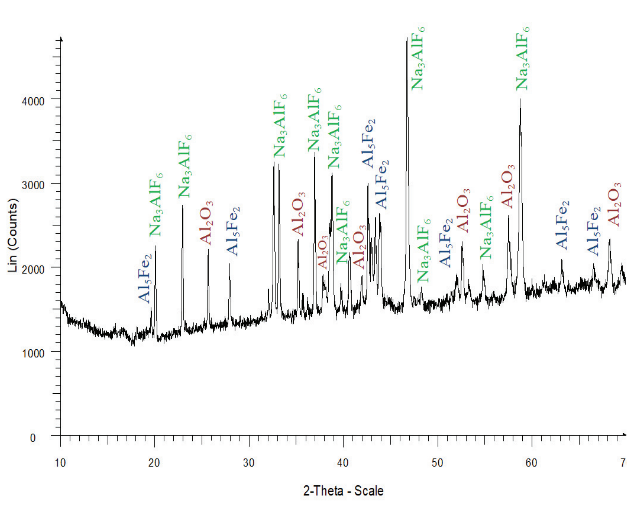
The samples after *TCT* were subjected to *XRD* to determine the phase composition of the diffusion layers. Figure 5, *a* shows the *XRD* pattern after boriding of *St3* steel, where *FeB* and Fe_2B phases were revealed on the surface. Single Fe_2B phase was distinguished after boriding of *3Cr2W8V* steel (Fig. 5, *b*).



a *b*

Fig. 5. XRD-pattern of the surface after boriding:
a – St3; *b – 3Cr2W8V*

Figure 6, *a* shows the *XRD* pattern after the aluminizing of *St3* steel, where Al_5Fe_2, Na_3AlF_6 and Al_2O_3 phases were established on the surface, while Al_5Fe_2, Na_3AlF_6 and Al_2O_3 were identified on the surface of *3Cr2W8V* steel.

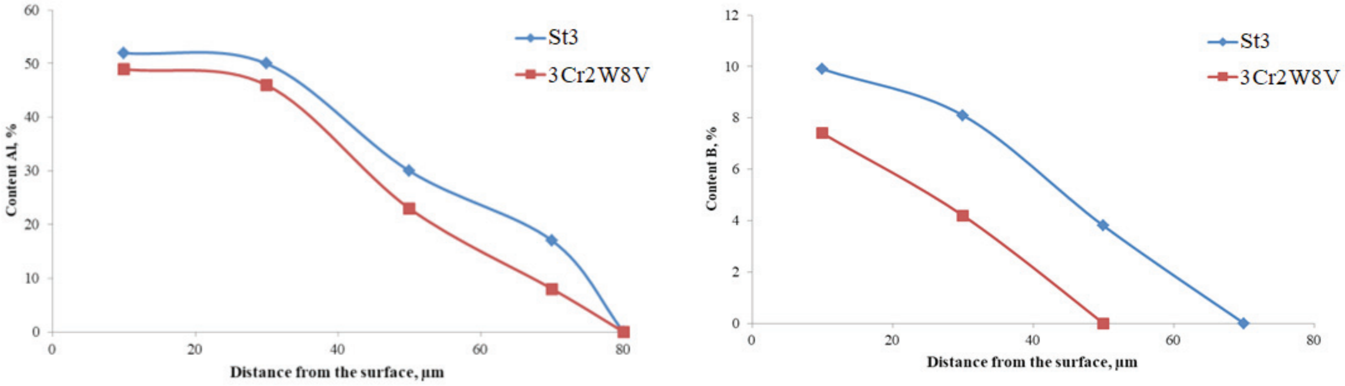


a

b

Fig. 6. XRD-pattern of the steel surface after aluminizing:
a – St3; *b – 3Cr2W8V*

The *EDS* analysis determined *B* and *Al* in the diffusion layer and transition zones. Figures 7, *a* and 7, *b* show *B* and *Al* distribution over the both steels, respectively. As it is seen on the graphs, boriding under the same conditions resulted in a slightly higher boron content (by 1–2 %) in the diffusion layer on *St3* steel compared to the alloy steel. Boron content is inversely proportional to the layer thickness on both steels (Fig. 7, *a*). A similar picture is observed during aluminizing of the studied samples. The aluminum content was higher by 2–7 % on *St3* steel compared to the alloy steel depending on the layer thickness (Fig. 7, *b*). It was established that the aluminum content was 3–5 % higher in the local extrema than in other areas of the layer on *3Cr2W8V* steel.



a

b

Fig. 7. Distribution of boron and aluminum over the layer thickness on the steels after boriding (*a*) and aluminizing (*b*) respectively

Conclusion

Based on the study, it was found that at a process temperature of 900 °C and a holding time of 2 hours after boriding, iron borides are formed on the surface of both steels. At the same time, both *FeB* and Fe_2B iron borides were revealed by *XRD* on *St3* steel and a single Fe_2B phase was found on *3Cr2W8V* steel.

Phases containing aluminum, such as Al_5Fe_2, Na_3AlF_6 and Al_2O_3, were formed after aluminizing of the both steels. The thickness of the obtained diffusion layers on the alloy steel was less than on the carbon steel, which was due to the alloying elements inhibiting the diffusion of boron and aluminum. The maximum microhardness of 1,920 HV was observed on *St3* steel after boriding, which is explained by the presence of both iron borides in its composition. The maximum value of microhardness reached 1,620 HV on *3Cr2W8V* steel. The microhardness of the both steels after aluminizing was almost the same and equaled to 1,000–1,100 HV.

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Conflicts of Interest

The authors declare no conflict of interest.