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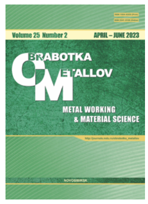

Structure and properties of low carbon steel after plasma-jet hard-facing of boron-containing coating

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ABSTRACT

Introduction. One of the effective thermochemical methods for increasing the hardness of steel is boronizing by diffusion of boron atoms into the steel surface at high temperatures. As a result of boronizing, coatings are formed on the steel surface, consisting of columnar crystals of *FeB* and Fe_2B. The volume fraction of phases and the thickness of the coatings depend on the heating temperature and the chemical composition of the base material and the saturating medium. The main disadvantage of these boronized layers is its high brittleness. Boronizing by plasma heating is one of the alternatives to the diffusion boronizing process to minimize the brittleness of the boronized layer. **The purpose of the work:** to form boride coatings on low-carbon steel using plasma-jet hard-facing. **The research methods** are: determination of the content of chemical elements using an electron probe micro-analyzer, metallographic studies, analysis of the phase composition of the boronized layer, as well as measurement of the microhardness of the coating after plasma-jet hard-facing. **In this work** boronized layers obtained on low-carbon steel 20 by plasma-jet hard-facing of a boron-containing coating are studied. Powdered amorphous boron was used as an alloying element. The parameter varied during plasma-jet hard-facing process is the current strength (120 A, 140 A and 160 A). **Results and discussions.** Based on the studies performed, it is found that it is possible to form boronized layers on the steel surface using plasma-jet hard-facing method. It is noted that the surface layer of the coating of the 1st and 2nd specimens after plasma-jet hard-facing has a heterogeneous structure, consisting of rows of different zones. The first zone has a hypereutectic structure, which consists of primary borides *FeB* and Fe_2B, located in the eutectic, consisting of Fe_2B and α-*Fe*. The second zone above the boundary with the base metal is represented by eutectic colonies composed of Fe_2B and α-*Fe*. The third specimen is characterized by a hypoeutectic structure consisting of boride eutectic and primary dendrites of the α-solid solution of boron in iron. The maximum hardness is fixed on the surface of the first specimen and is 1,575 HV. The depth of the hardened layer increases with increasing current, but the hardness value and boron content decrease after treatment. The slight hardness gradient observed over the depth of the coating, as well as the gradual decrease in hardness due to the presence of the transition zone, are considered favorable for good adhesion of the boronized layer to the surface of the base material.

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Introduction

It is known that during the operation of steel parts and tools, the surface layers are subjected to the most intense external influences, therefore, the structure and properties of the surface layers often have a decisive influence on the performance of products as a whole. Therefore, the formation of surface layers with the necessary functional properties is more profitable than the production of steel with similar properties, and in some cases it is the only technically possible solution [1–3].

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Boronizing is one of the promising methods for increasing the surface hardness and wear resistance, oxidation and corrosion resistance of machine building parts. There are several boronizing methods, such as powder, chemical, and electrolytic ones [4–7]. It has been noted that the process of diffusion boronizing is characterized by a long duration (8–10 hours) and a small hardening depth (less than 200 μm) [8–10]. In addition, saturation of the steel surface with boron usually results in the formation of *FeB* and Fe_2B, which has an acicular microstructure. This microstructure makes the boride layer very brittle. This does not allow efficient use of boronized parts when subjected to impact and high local loads during operation. The destruction of the acicular structure on the surface leads to the formation of a globular structure, which can significantly increase the strength and plasticity of the surface [11].

Saturation of the steel surface with boron using a laser, an electron beam, or a plasma arc [12–15] makes it possible to reduce the boronizing process to 0.1–1 min and obtain a hardened layer depth in the range of 1–5 mm. In [16], *CrB* powder was used to alloy the surface of carbon steel using a laser. The results showed that at low scanning speed (10 mm/s) the microstructure and properties of the alloyed layer are uniform. The authors of [17] used a laser to modify the structure of borated steel without disturbing the microstructure and properties of the base metal. It was found that laser surface modification with a power of 250 W reduces the hardness gradient of the alloyed layer to the base metal and leads to a significant increase in the ductility and toughness of the steel. The authors of [18] investigated the boronizing process and noted that laser boronizing of mild steel can be performed faster and without any pre-treatment. It has been found that the most desirable microstructure for laser boronizing of *AISI 1018* steel is Fe_2B, which has a high hardness in the range of 1,300–1,700 HV and a compressive stress on the machined surface. Powdered boron carbide was used for surface hardening using an electron beam [19]. The authors noted that the hardened layer after treatment has a dendritic structure and a surface hardness that is more than 6 times higher than the hardness of the base metal. The authors of [20] studied the structure and properties of boride coatings formed on *AISI 1018* steel using a plasma heating source. According to the results of the study, it was noted that the thickness of the coatings ranged from 1 to 1.5 mm, the hardness was from 400 to 1,600 HV. The wear rate of boronized coatings is approximately four orders of magnitude lower than that of the steel base. Based on the results of literature analyzes, it was noted that boride coatings on a steel base can be obtained using laser, electron beam, and plasma arc heating sources. In addition, in particular, there are very few works using plasma surface heating for steels boronizing.

The purpose of the work is the formation of boride coatings on low-carbon steel using plasma plasma-jet hard-facing technology. To achieve this purpose, microscopic investigation, phase composition analysis and microhardness testing of deposited coatings were carried out.

Methodology of research

Steel 20 (0.17–0.24% *C*, 0.17–0.37% *Si*, 0.35–0.65% *Mn*, ≤ 0.25 % *Ni* , ≤ 0.04 % *S*, ≤ 0.04 % *P*, ≤ 0.25 % *Cr*, ~98 % *Fe*) was used as the base material. Steel plates with a size of 75×15×15 mm were cut and polished with sandpaper (with an increase in grain size up to 1,200 grit). The suspension was prepared by mixing amorphous boron powder with *BF-6* adhesive with a weight ratio of 1:1 and preliminarily applied to the surface of each plate. The thickness of the coating is fixed at 1 mm. After that, the coated plates were dried in a furnace at a temperature of 60 °C for 2 hours. Equipment for plasma-jet hard-facing is schematically shown in figure 1. In all processing modes, voltage (30 V), transporter table movement speed (4 mm/s), distance between plate surface and electrode (3 mm), nozzle diameter (5 mm) and shielding gas flow rate (18 l/min) are permanent. The current is used as a variable parameter (Table).

The microstructure of the hard-faced layers was studied using an optical microscope *MET-2* and a two-beam scanning microscope (multibeam system) *LV-4500*. To determine the boron content in the hard-faced layer, the electron probe micro-analyzer method was used.

The electron probe microanalyzer method is as follows: a beam of highly accelerated electrons is incident on a small surface (~1 μm^2) of the sample, then the outgoing X-rays are selected based on its wavelength using the received crystal diffraction condition, and then the element concentration is quantified by

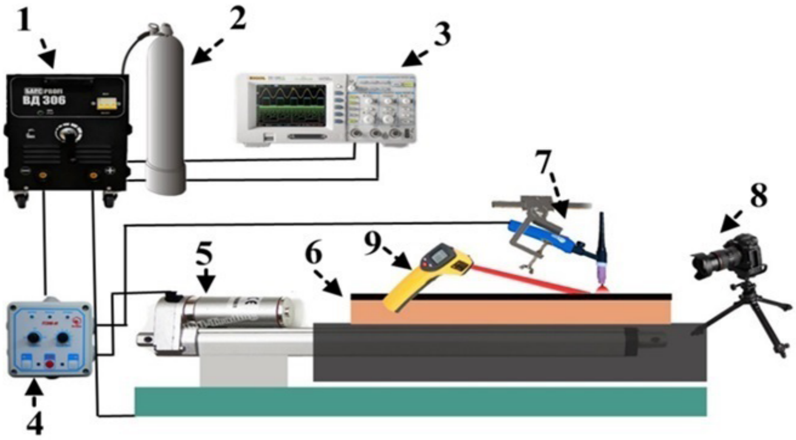


Fig. 1. Plasma-jet hard-facing scheme

1 – power source; *2* – argon bottle; *3* – oscillation detector; *4* – control block; *5* – electric motor; *6* – specimen with smearing, *7* – plasma torch; *8* – camera, *9* – infrared thermometer

Parameters of the plasma-jet hard-facing process

Specimen No.	Current, A	Processing method
1	120	one track
2	140	
3	160	

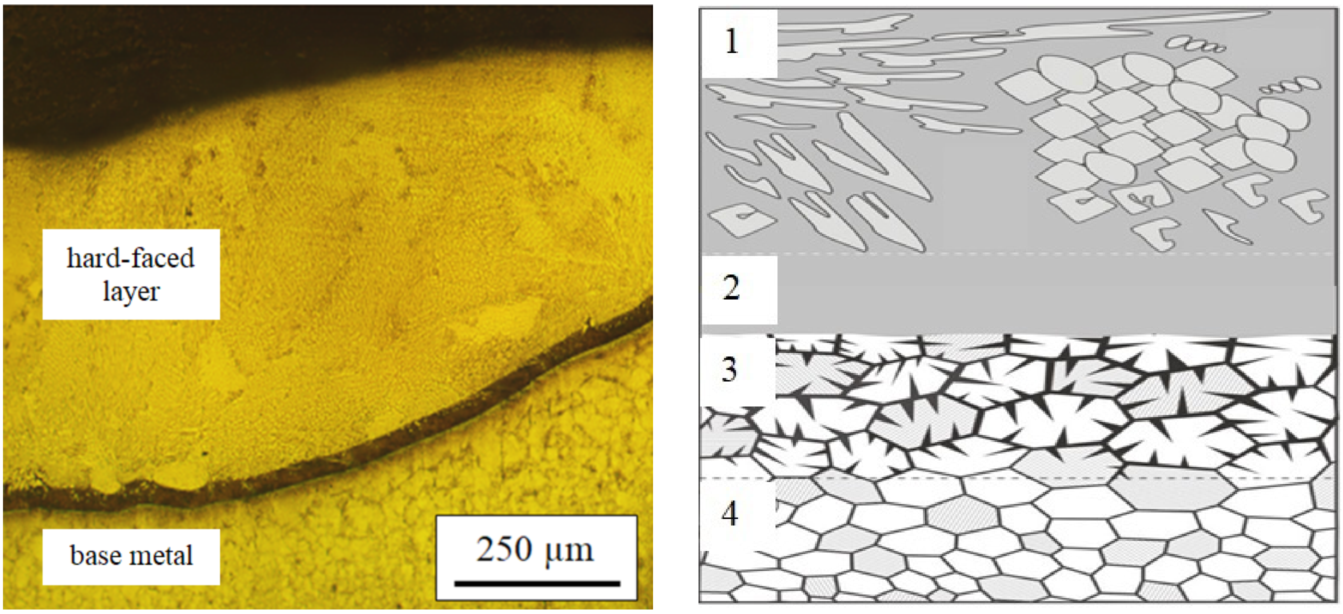
comparing the intensities of the characteristic X-rays from each element that is present in the sample with the intensity of the same radiation emitted by the standard. The study of the phase composition of coatings after plasma-jet hard-facing was carried out on an X-ray diffractometer *Shimadzu XRD-7000* using *CuKα* radiation. The samples were scanned in step-by-step scanning mode in the range of 5°–85° with 5° steps at 40 kV and 40 mA. The microhardness of the alloyed layer was measured using a *Shimadzu HMV-2* microhardness tester.

Results and discussion

In the process of samples' microscopic investigation, it was found that the method of plasma melting of a coating containing amorphous boron and a binder of *BF-6* glue makes it possible to form coating layers without cracks and pores. Figure 2, *a* shows the microstructure of the cross section of the first sample after plasma-jet hard-facing.

The first zone is characterized by the presence of a hypereutectic-type structure, which consists of primary crystals of *FeB* and Fe_2B of various morphology, located in a eutectic matrix consisting of Fe_2B and α-*Fe* (figure 3). The boride morphology varies from oval (figure 4, *a*) to columnar (figure 4, *b*). In addition, iron borides with incomplete overgrowth of faces were observed in the hard-faced layer (figure 4, *c*).

In the region of the coating near the base metal, the structure of the layer 100 µm wide is represented only by eutectic colonies (figure 4, *d*), because the boron concentration is not sufficient to isolate borides. At the bottom of the hard-faced layer, a heat-affected zone is formed, characterized by the presence of coarse grains, the formation of which is due to heating to high temperatures. Next is a zone with the structure of the base metal. The boron content in the hard-faced layer is 12.35 %.



a *b*

Fig. 2. Micrograph (*a*) and scheme (*b*) of the 1st specimen cross section structure after plasma-jet hard-facing: *1* – hypereutectic zone with iron borides of various structures; *2* – eutectic zone; *3* – heat affected zone; *4* – base metal

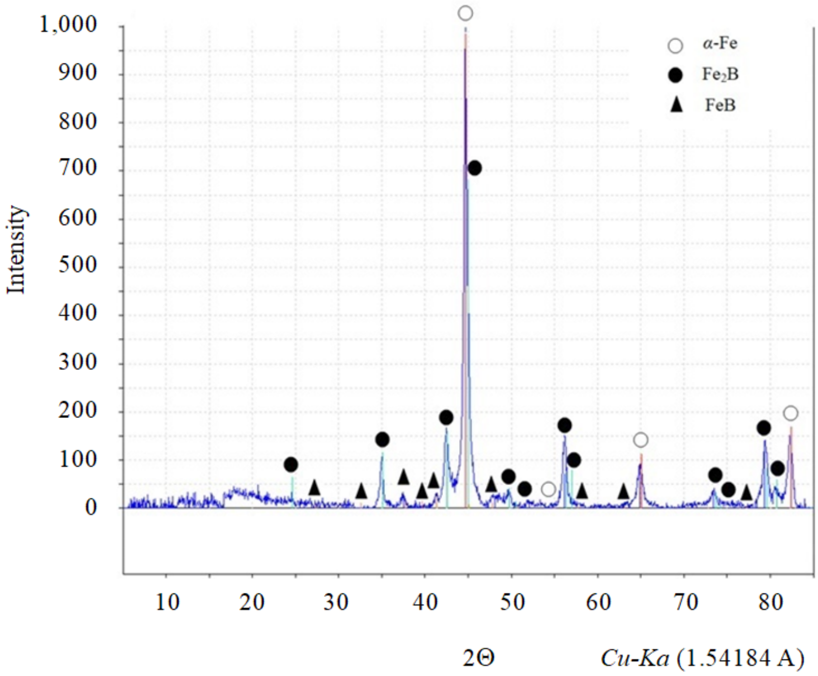


Fig. 3. X-ray pattern of the first specimen after plasma-jet hard-facing

A heterogeneous structure of the surface layer of the second specimen after plasma-jet hard-facing was also obtained (Fig. 5). But it is noted that the proportion of primary borides in the hard-faced layer is much smaller. The boron content in the hard-faced layer decreases and amounts to 9.23%. The microstructure of the coating layer consists of primary iron borides FeB and Fe_2B located in a eutectic matrix consisting of Fe_2B and α-Fe, as shown in figure 5.

X-ray analysis shows the presence of primary FeB and Fe_2B borides on the steel surface after plasma-jet hard-facing (figure 6). In the lower part of the coating near the boundary with the base metal (figure 5, *d*),

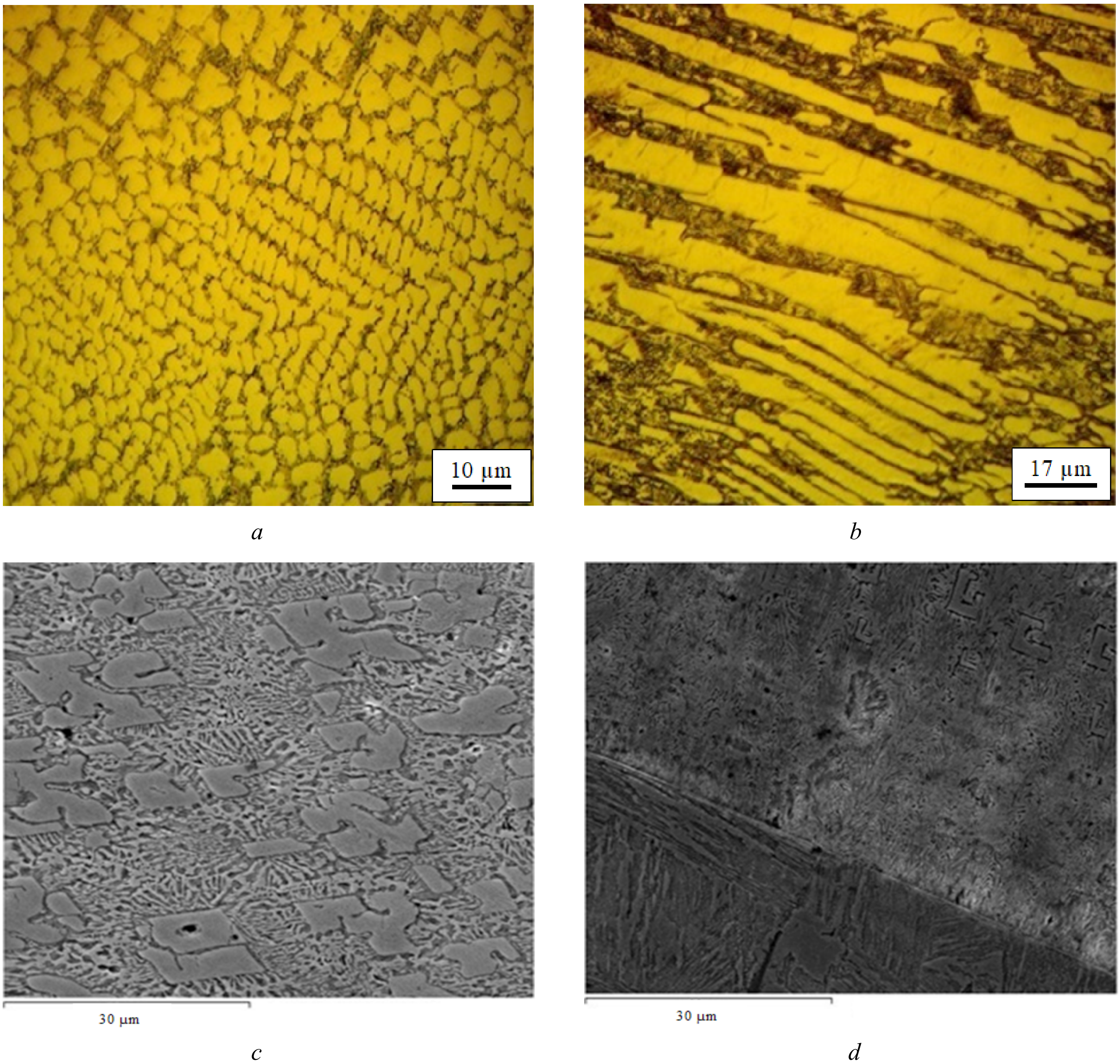


Fig. 4. Microstructure of the 1st specimen after plasma-jet hard-facing:
a, *b*, *c* – the upper part of coating; *d* – the lower part of the coating near the boundary with the base metal

the microstructure is also represented by eutectic colonies of Fe_2B and α-*Fe*, but the width of this layer has increased and is 200 µm.

Figure 7 shows the microstructure of the hard-faced layer of the third specimen after plasma-jet hard-facing. It has a hypoeutectic structure consisting of boride eutectic and primary dendrites of a α-solid solution of boron in iron.

According to the X-ray analysis data (figure 8), the main phases of the coating are Fe_2B and α-*Fe*. The boron content in the hard-faced layer is 3.4 %. It can be seen that these microstructures are in a good agreement with these phase diagrams when considering binary phase diagrams of *Fe–B* [18]. It is known that alloys of iron with boron are of eutectic type, where the eutectic is formed by a solid solution of α-*Fe* and Fe_2B. At a boron concentration of 3.83 wt.%, the alloy is 100 % eutectic.

In the course of studying the microstructure of the hard-faced layer after plasma-jet hard-facing, the boron content was determined by the layer depth using the electron probe micro analyzer method. The results of determining the boron content by the depth of the hard-faced layer are shown in figure 9. It can

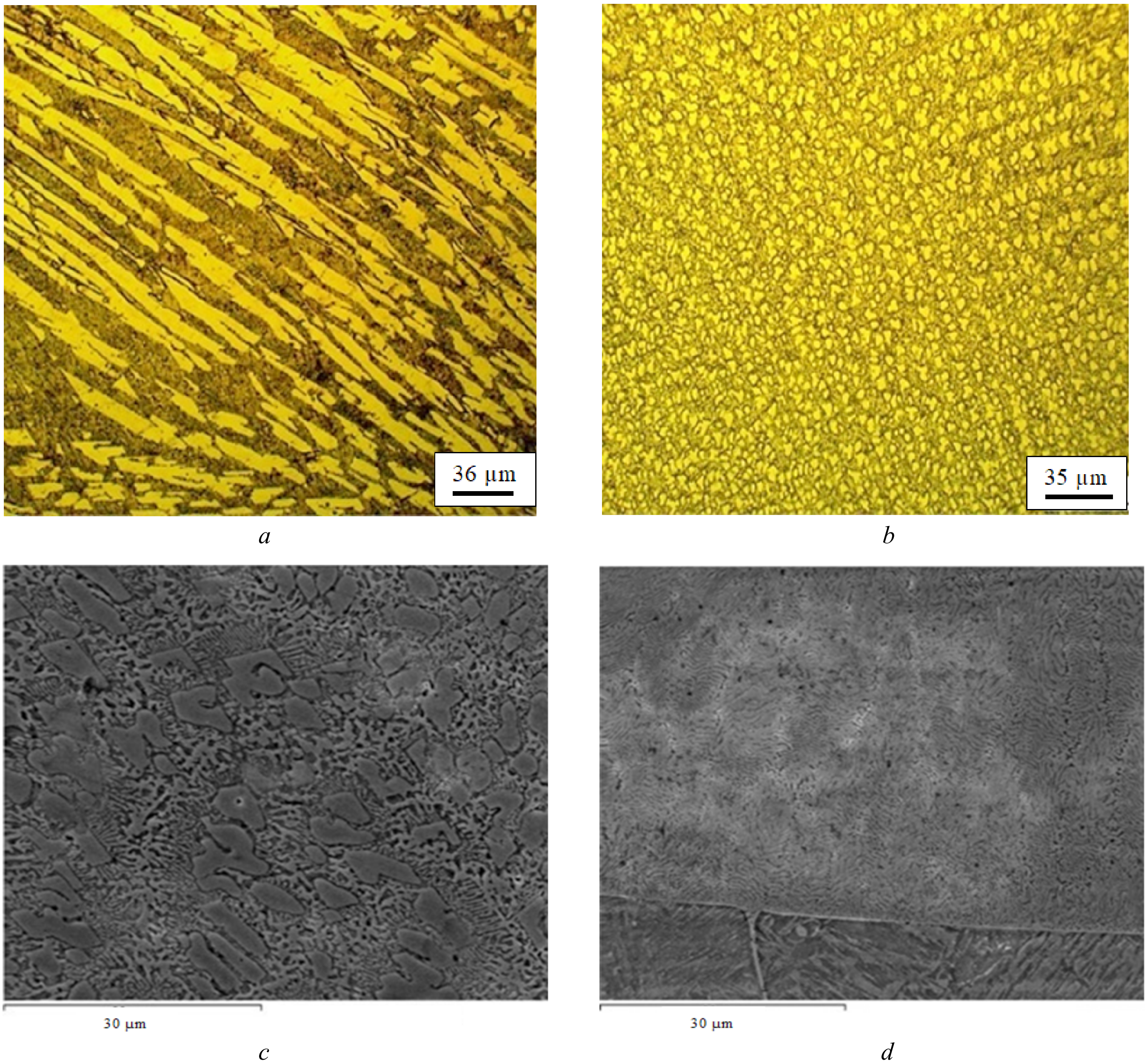


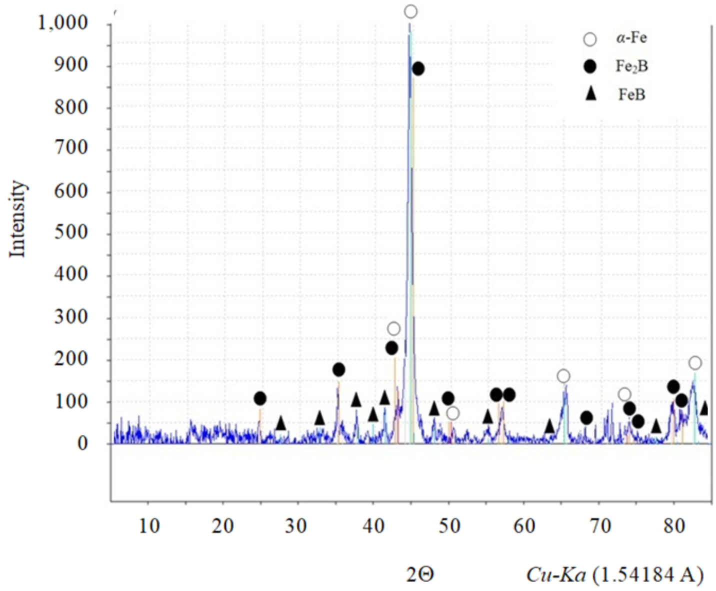
Fig. 5. Microstructure of the 2nd specimen after plasma-jet hard-facing:
a, *b*, *c* – the upper part of coating; *d* – the lower part of the coating near the boundary with the base metal

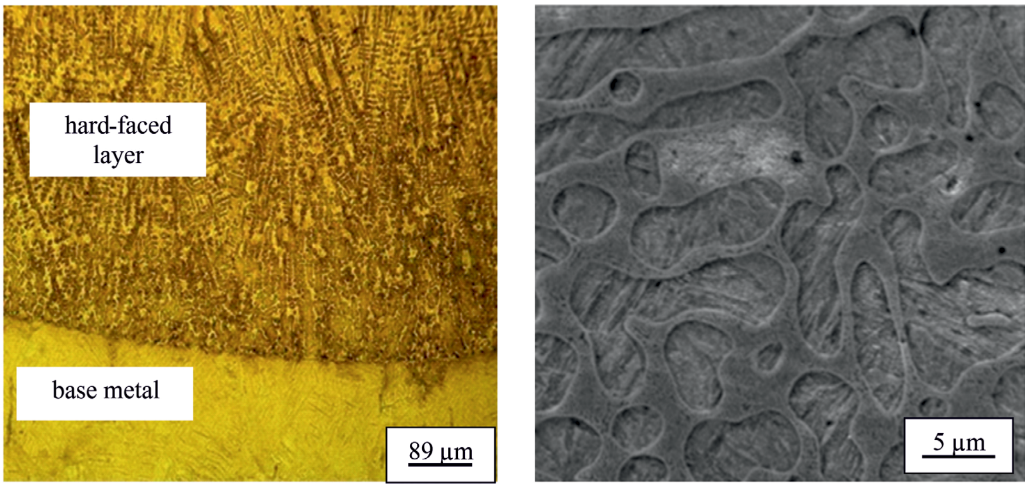
be seen from the resulting diagram that the boron content in the hard-faced layer decreases from the coating surface to the base metal. At the same time, in the hard-faced layer of the first specimen, the boron content is higher by 1.5–2 % compared to the second specimen, and higher by 7–8 % compared to the third specimen, depending on the depth of the hard-faced layer.

Figure 10 shows the distribution of microhardness over the depth of the boronized layer at various current after plasma boronizing. With an increase in current from 120 A to 160 A, the hardened depth increased from 0.625 mm to 1.95 mm. The maximum hardness of 1,547 HV for *Steel 20* was observed at a depth of 0.075 mm from the layer surface, which is typical for boronizing due to the formation of solid iron borides. Iron boride particles are a high-strength phase, which determines the degree of hardening in the alloyed layer. These higher hardness values are associated with a higher boron content, which led to the formation of a large amount of primary FeB and Fe_2B borides.

An increase in current to 140 A leads to an increase in the thickness of the coating to 1.125 mm and the maximum hardness drops to 1,293 HV. This is explained by the fact that the higher the current, the greater

Fig. 6. X-ray pattern of the 2nd specimen after plasma-jet hard-facing





a *b*

Fig. 7. Microstructure of the 3rd specimen after plasma-jet hard-facing:
a – optical microscopy; *b* – scanning electron microscopy

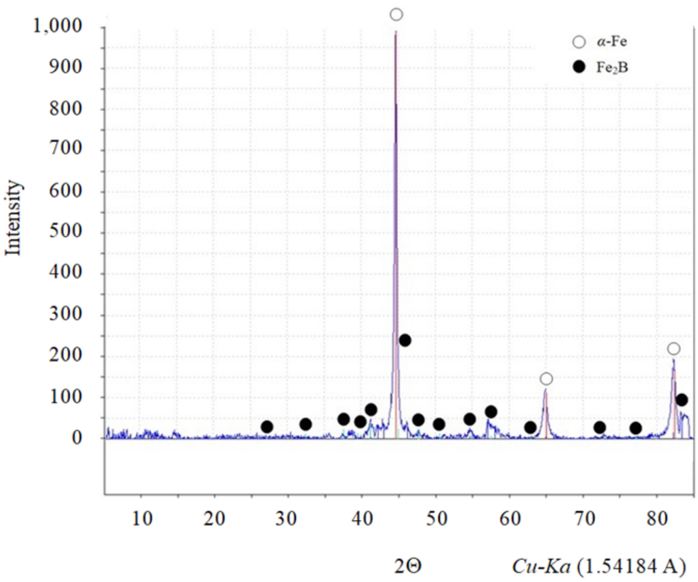


Fig. 8. X-ray pattern of the 3rd specimen after plasma-jet hard-facing

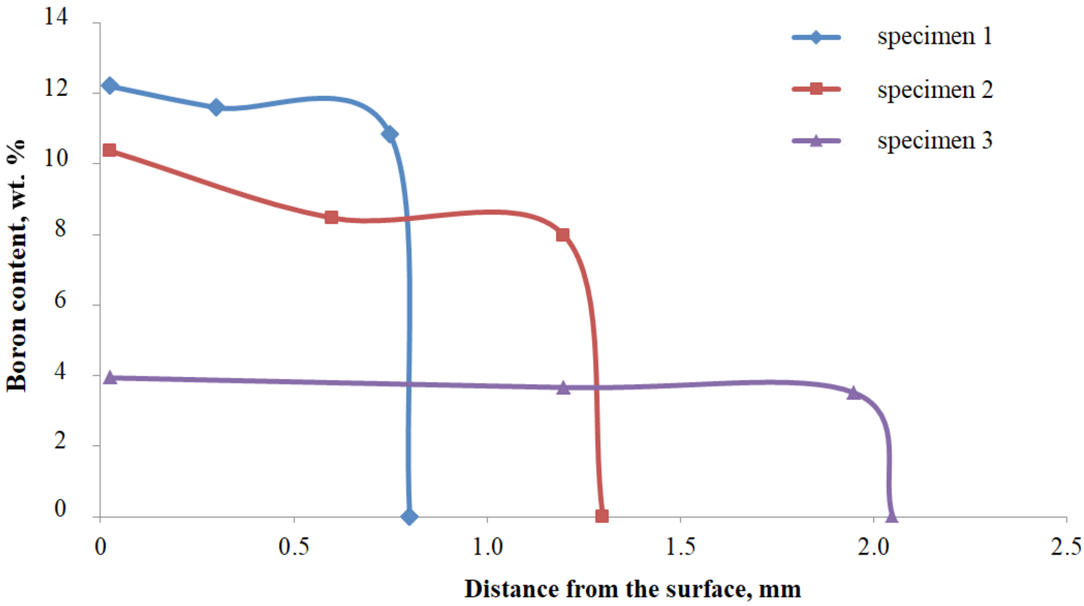


Fig. 9. Distribution of boron over the layer depth on steels after plasma-jet hard-facing

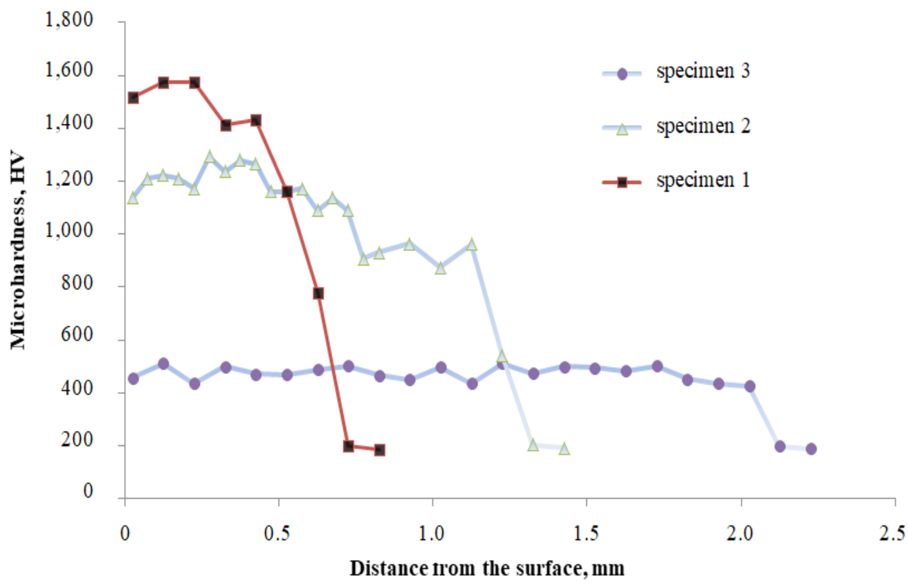


Fig. 10. Distribution of microhardness over the depth of hardened layers

the dilution of the smearing mixture with the base material. As a result, the concentration of boron in the hard-faced layer decreased, and vice versa, the proportion of the eutectic component increased. The lowest value of the hardness of the alloyed layer is 452 HV (obtained at a current of 160 A), because the surface layer after boronizing has a hypoeutectic structure and the lowest boron content.

It is interesting to note that the slight hardness gradient observed over the depth of the coating, as well as the gradual decrease in hardness due to the presence of the transition zone, are considered favorable for good adhesion of the boride layer to the surface of the base material. For example, the sharp jump in hardness between the boride layers and the base metal observed in diffusion boronized layers is considered to be one of the main causes of poor adhesion leading to peeling and splitting of coatings.

Conclusions

1. In the course of the conducted studies, it is found that it is possible to obtain boride layers on the surface of steel using the technology of plasma-jet hard-facing of a boron-containing coating.

2. It is noted that the surface layer of the coating of the first and second specimens after plasma-jet hardfacing has a heterogeneous structure, consisting of rows of different zones. The first zone has a hypereutectic structure, which consists of primary borides *FeB* and Fe_2B, located in the eutectic, consisting of Fe_2B and *α-Fe*. The second zone above the boundary with the base metal is represented by eutectic colonies of Fe_2B and *α-Fe*. The third specimen is characterized by the hypoeutectic structure of the boride eutectic and primary dendrites of the α-solid solution of boron in iron.

3. The maximum microhardness of the alloyed layer is fixed at a current strength of 120 A and is 1,575 HV. The depth of the hardened layer increases with increasing current, however, the hardness value and the boron content decreases. The slight hardness gradient observed over the depth of the coating, as well as the gradual decrease in hardness due to the presence of the transition zone, are considered favorable for good adhesion of the boride layer to the surface of the base material.

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Conflicts of Interest

The authors declare no conflict of interest.