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INFLUENCE OF MICROALLOYING WITH BORON ON THE STRUCTURE AND PROPERTIES OF DEPOSITED METAL OF THE TYPE OF TOOL STEEL 25Kh5FMS

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ABSTRACT

In the work, the influence of different amounts of boron microadditives on the structure and operational properties of metal of the type of tool steel 25Kh5FMS, produced by arc surfacing using the experimental flux-cored wires, was experimentally determined. Microalloying additives were introduced directly into the charge of experimental flux-cored wires during their manufacture. It was found that microalloying of the deposited metal of the type of steel 25Kh5FMS with boron in the amount of 0.007–0.04 % does not deteriorate the quality of deposited beads formation and separation of the slag crust. At the same time, when the boron content in the deposited metal is ≥ 0.02 %, the formation of a large number of crystallization cracks is observed, which has an extremely negative effect on its operational properties. Moreover, it was experimentally found that the introduction of boron microadditives in the amount of 0.007–0.01 % to the deposited metal of the type 25Kh5FMS leads to an increase in its heat resistance and wear resistance at elevated temperatures by 1.2–2.0 times. With an optimal content of microalloying additives, a refinement of the structure of the deposited metal, some increase in microhardness and, probably, the formation of complex spherical carboborides in the alloy matrix occur. In view of the obtained data, it is recommended to use boron in the deposited metal of the type of tool steel 25Kh5FMS in the amount of 0.007–0.01 % in order to improve its operational properties.

KEYWORDS: arc surfacing, microalloying, deposited metal, flux-cored wire, wear resistance, heat resistance, microstructure

INTRODUCTION

Nowadays, in our country and abroad, a large number of materials in the form of solid and flux-cored wires, strips and coated electrodes for arc surfacing of parts of machines and mechanisms, operated in the conditions of different types of wear, cyclic mechanical and thermal loads, corrosion, etc., were developed [1–5]. In essence, the technical and economical capabilities to increase the operational properties of the deposited metal by conventional additional alloying of electrode materials are almost exhausted.

Great opportunities in the control of the structure and properties of the deposited metal are opened up by the use of microalloying and modification, which have almost not been used in surfacing production until now [6, 7]. Only certain works are known, mainly aimed at solving practical problems, such as, for example, for surfacing of propeller shafts of sea vessels [8] and other pasrts [9–11].

The aim of the work was to investigate the effect of boron microalloying on the structure and operational properties of metal of the type of tool semi-heat-resistant steel 25Kh5FMS, produced by arc surfacing using flux-cored wires with a charge containing microalloying additives.

MATERIALS USED TO CONDUCT STUDIES

For the experiments, a charge composition was calculated and four experimental flux-cored wires for surfacing were manufactured, which provide a deposited metal of the type of tool steel 25Kh5FMS. As a microalloying additive, FKhB-1 master alloy was used, which contains 12 % of boron. This master alloy in the form of powder was added directly to the charge of flux-cored wires during their manufacture with such calculation as to obtain the boron content in the charge of flux-cored wires from 0.01 to 0.1 %. As was shown in [6], such a method of introducing microalloying or modifying additives from a technological and economic point of view is the simplest and most rational in arc surfacing. As a reference, the flux-cored wire PP-Np-25Kh5FMS was used without adding microallolοying additives. The diameter of all designed wires is 1.8 mm, the fill factor is 25 %. Surfacing of the experimental specimens was performed under the flux AN-26P.

PROCEDURES AND SPECIMENS FOR CONDUCTING STUDIES OF OPERATIONAL PROPERTIES OF DEPOSITED METAL

Hot deforming tools during operation are mainly worn as a result of friction of metal against metal at elevated temperatures. In addition, as a result of periodic con-

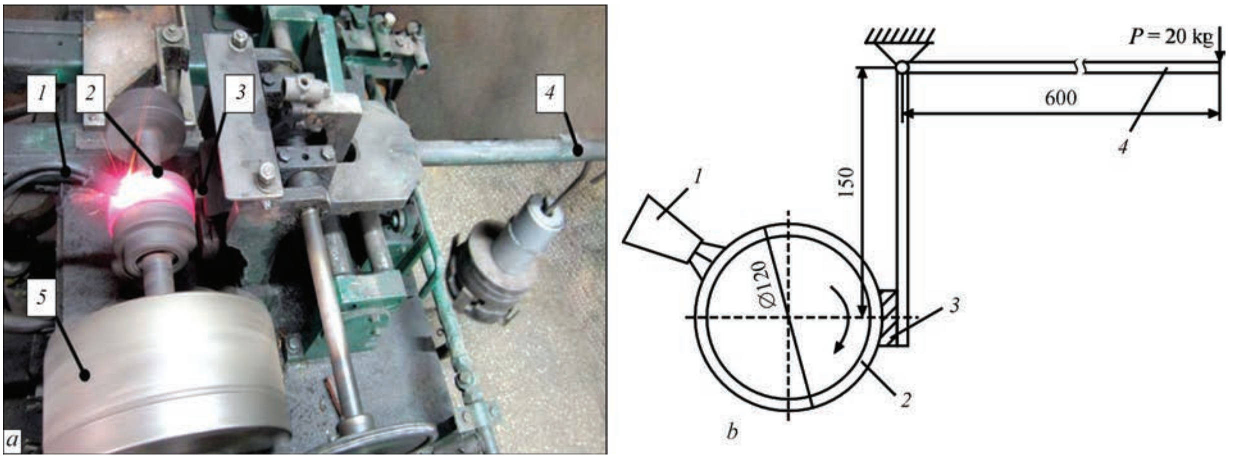

Figure 1. Appearance (*a*) and schematic diagram (*b*) of the installation unit for studying wear resistance of the deposited metal in friction of metal against metal at elevated temperatures: *1* — gas torch for heating of the ring (counterbody), which wears out the specimen; *2* — ring (counterbody); *3* — worn specimen; *4* — lever with loads for clamping the specimen to the ring (counterbody); *5* — drive for rotation of the ring (counterbody)

tact with the workpieces heated to high temperature, in the deposited metal, thermal fatigue cracks may occur. To conduct studies of wear-resistance during friction of metal against metal at elevated temperatures and thermal resistance of the deposited metal, an experimental block-module installation was used [12].

PROCEDURE FOR STUDYING WEAR IN FRICTION OF METAL AGAINST METAL AT ELEVATED TEMPERATURES

The main research parameters include specific pressure on a tested deposited specimen, heating temperature of this specimen, speed of relative movement of friction elements (friction rate), material of the ring (counterbody), which wear out the specimen, heating temperature of the ring.

In Figure 1, *a* the photo of the installation unit, and in Figure 1, *b* principal scheme of studying wear resistance of the deposited metal in friction of metal against metal at elevated temperatures are shown. The correlation of the shoulders of the lever mechanism at a load of 20 kg provides clamping of the specimen to the ring, which wears the specimen with a force of 800 N. When the cylindrical surface of the heated ring gets in contact with the plane of the specimen, the pressure at the point of contact is determined by the formula

$$P_{\mathrm{cl}} = 0.798\sqrt{\frac{\rho}{D\left(\frac{1-\mu^2}{E_1}+\frac{1-\mu^2}{E_2}\right)}},$$

where $\rho = P/l$; P is the clamping force (800 N); l is the width of the specimen (10 mm); D is the diameter of the ring (120 mm).

Accepting the values of the Poisson's ratio and elasticity modules for heated steel and tested specimen equal respectively to $\mu = 0.3$; $E_1 = 25000$ MPa; $E_2 = 20000$ MPa, we obtain the value of specific pressure of 100 MPa. The friction rate was 20–22 m/min, which corresponds to the most used modes during hot deformation of metals.

The ring, which wears out the specimen, was heated by oxyfuel flame. Due to a rough certain ratio of gas and oxygen consumption, the temperature of the ring was maintained by constant — 950–980 °C, which was periodically controlled by means of the optical pyrometer. The temperature on the surface of the specimen in the area of contact of the specimen and the ring was approximately 600 °C. The wear resistance of the specimen is determined by weight loss before and after the test, the average value of which is calculated by three specimens of one type.

PROCEDURE OF RESEARCH OF DEPOSITED METAL THERMAL RESISTANCE

During evaluation of heat resistance, the cycles of heating and cooling of the deposited specimens were repeated till the initiation of thermal fatigue cracks or achieving a certain degree of cracking. In this case, the degree of thermal stability is a number of cycles before achieving these values. The installation unit for the study of heat resistance of the deposited specimens is shown in Figure 2.

The specimen being investigated is installed in the frame of the installation so that its deposited polished surface is directed to the heating source, in capacity of which, a oxyfuel torch is used. The reciprocating motion drive provides movement of the mandrel with a specimen fixed in it from the heating source to the place, where the specimen is cooled with water.

A uniform heating by the gas torch is successful in the spot on the surface of the specimen with a diameter of ≈ 15–20 mm. The heating lasts 12 s, the cooling with a jet of water lasts 8 s. Under these conditions, the heating temperature of the specimen surface is stabilized before the 10th cycle and is in the range of 630–690 °C. Cooling of the specimen with water is carried out to 60–80 °C. The heating-cooling cycles are repeated before the appearance of the network of thermal cracks visible with a naked eye, after which the test was stopped, the deposited surface of the specimen was cleaned and photographed.

After that, to determine the depth and nature of propagation of thermal cracks in the deposited metal, the specimens of all types were continuously loaded by the cycles of heating-cooling until reaching 200 test cycles. Then, the specimens were cut perpendicular to the deposited surface, macrosections were made and the depth of crack propagation was measured. As a result, the heat resistance of each type of the deposited specimen was evaluated by two values — a number of cycles before appearance of a network of cracks, and the depth of their propagation upon reaching 200 cycles of heating-cooling. The determination of both values was calculated as an average value of three specimens of one type.

Metallographic examinations of the specimens of the deposited metal were performed according to standard methods. The specimens were prepared on high-speed polishing wheels using diamond pastes of different dispersion. The structure of the deposited metal was detected by electrolytic etching in a 20 % aqueous solution of chromic acid. Microstructure examinations were carried out in the metallographic optical microscope Neophot-32 at a magnification ×200. The hardness of phase components was measured in the M-400 microhardness meter of Leco Company, the load was 1 N, the load time was 10 s. Digital images of microstructures were obtained using the Olympus C-500 camera. The depth of thermal cracks was determined on produced macrosections in the metalographic MIM-7 microscope, equipped by the digital video eyepiece SIGETA MCMOS 3100 at a magnification ×90.

MANUFACTURE OF SPECIMENS, CONDUCTING EXPERIMENTAL STUDIES AND DISCUSSING THEIR RESULTS

To determine the impact of boron microalloying on welding and technological properties of flux-cored wires and the quality of the deposited metal formation, electric arc surfacing using experimental flux-cored wires PP-Np-25Kh5FMS on plates of 40Kh steel was performed. The surfacing of all specimens was performed under the flux AN-26P at the same mode: current — 220–230 A, voltage — 36–37 V, deposition rate — 25 m/h. The surfacing was performed with sin-

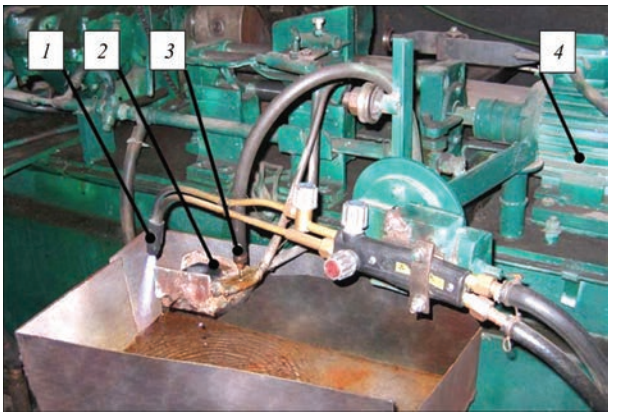

Figure 2. Appearance of the installation unit for studying heat resistance of the deposited specimens: *1* — gas torch for heating of the specimen; *2* — tested specimen; *3* — hose for supplying water that cools the specimen; *4* — drive for movement of the specimen

gle beads with an overlapping of approximately 50 %. In order to avoid the effect of mixing base metal, surfacing of each specimen was performed in four layers.

The appearance of the specimens after surfacing is shown in Figure 3, *a*, from which it is seen that the quality of metal formation deposited by all experimental wires is almost the same. The quality of slag crust separation in all cases was also at the same level and was satisfactory. After surfacing, the surface of the specimens was polished and investigated for the presence of pores, cracks and other defects (Figure 3, *b*). From the deposited specimens, templates were also cut out and transverse macrosections were prepared (Figure 4).

From the abovementioned figures it is seen that in all the deposited specimens the fusion line is clear, defects in the form of lacks of fusion, pores, etc. are absent. However, ≥ 0.02 % increase in boron content leads to the appearance of crystallization cracks in the deposited metal, which mostly pass through all the deposited layers and reach the base metal, but do not go into it.

Table 1 shows the data of X-ray spectral analysis of the boron content in the deposited metal, as well as the impact of boron microalloying on its hardness (specimens Nos 1–4). It was experimentally determined that in submerged-arc surfacing by flux-cored wires containing FKhB-1 master alloy, up to 70 % of boron goes into the deposited metal, which leads to a gradual increase in hardness of the deposited metal of the type of steel 25Kh5FMS. The additions of FKhB-1 master alloy do not deteriorate its welding and technological characteristics and do not affect the quality of the deposited metal formation and separation of the slag crust. At the same time, as is noted above, at a boron content in the deposited metal being ≥ 0.02 %, the appearance of a large number of cracks was noted.

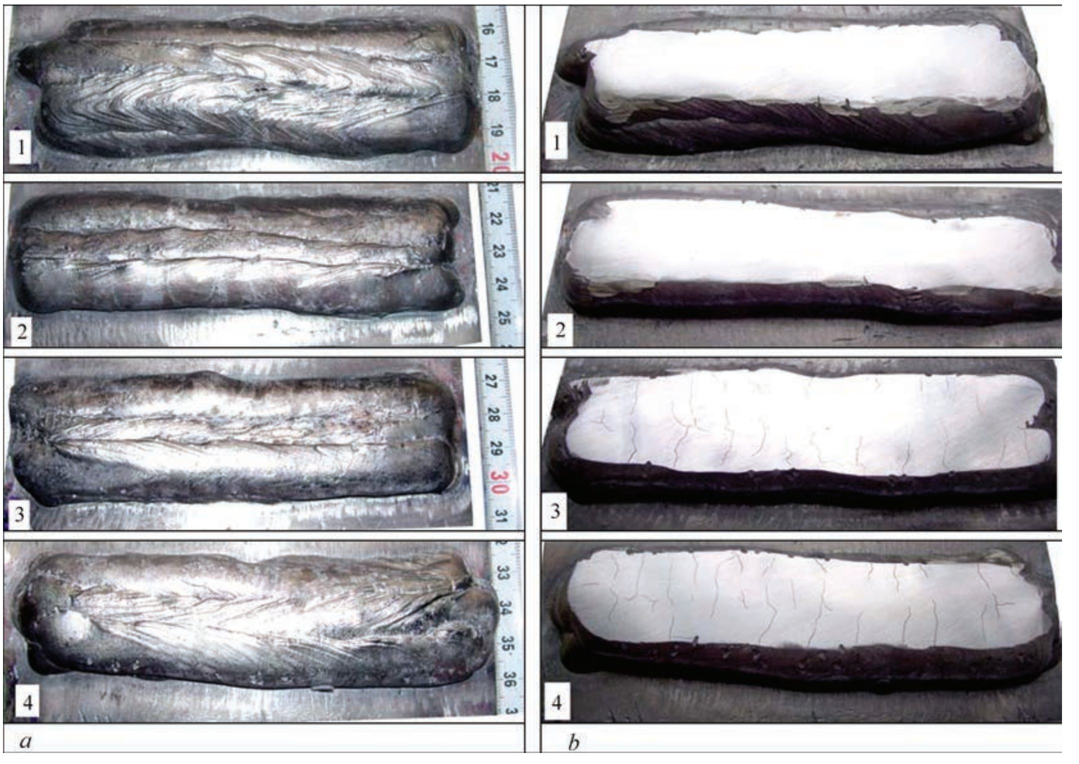

Figure 3. Appearance of the specimens of steel 40Kh after surfacing (*a*) and mechanical treatment (*b*). Boron content in the deposited metal, %: *1* — 0; *2* — 0.007; *3* — 0.02; *4* — 0.04

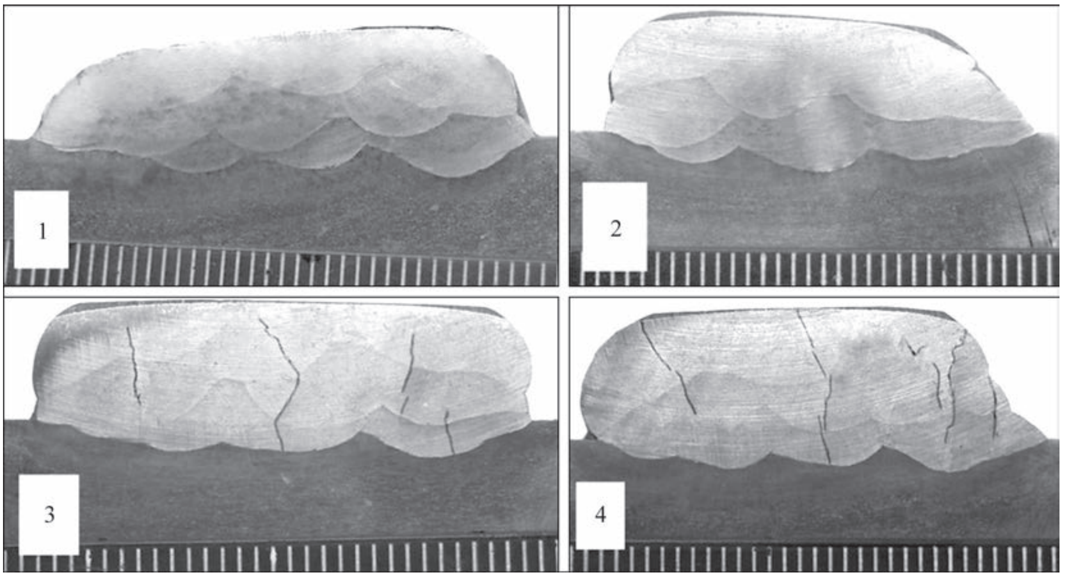

Figure 4. Transverse cross-sections of the deposited metal with different boron content, %: *1* — 0; *2* — 0.007; *3* — 0.02; *4* — 0.04

Table 1. Hardness of metal, deposited using experimental flux-cored wires of the type PP-Np-25Kh5FMS with different boron content

Specimen number	Mass fraction of boron in the deposited metal, %	Hardness of the deposited metal
1	–	50–54
2	0.007	54–55
3	0.02	54–56
4	0.04	55–57

Metallographic examinations of metal of the type of steel 25Kh5FMS, deposited by experimental flux-cored wires, showed that the structure of the deposited metal in its central part in the specimens of all types is cast, consists of columnar crystallites oriented in the direction of heat removal (Figure 5). The width of crystallites in the studied specimens is slightly different and has the following sizes: specimen No. 1 — 40–45 μm; specimen No. 2 — 20–22 μm; specimen No. 3 — 18–20 μm; specimen No. 4 — 15–20 μm. Thus, the introduction of boron microadditives into

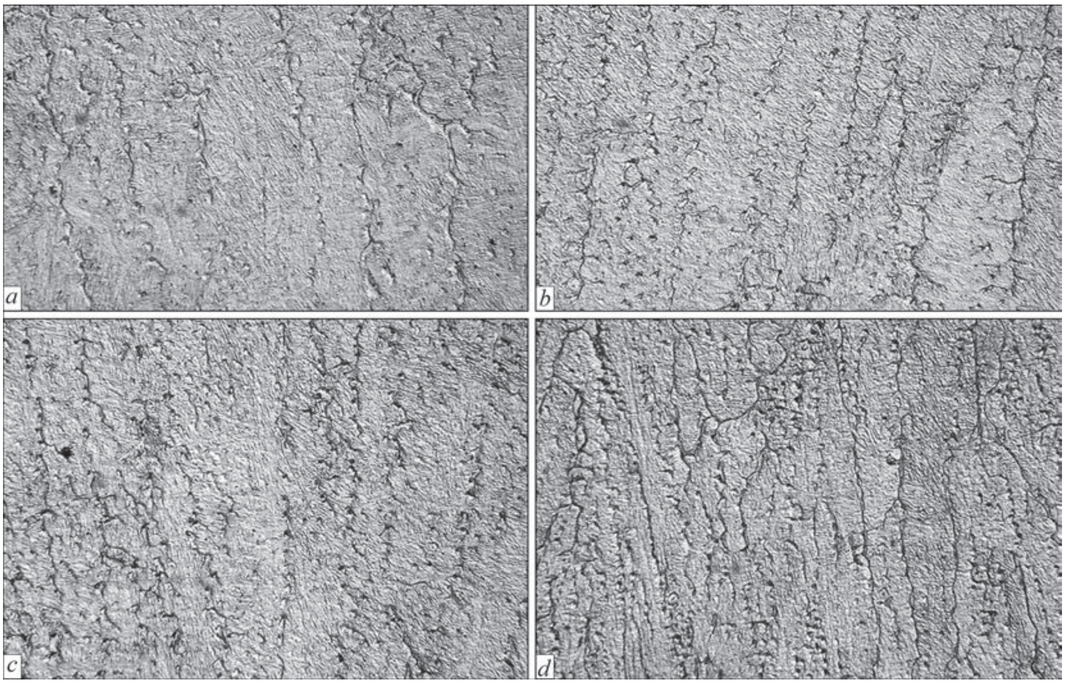

Figure 5. Microstructure (×200) of the central part of the deposited metal with different boron content, %: *a* — without boron; *b* — 0.007; *c* — 0.02; *d* — 0.04

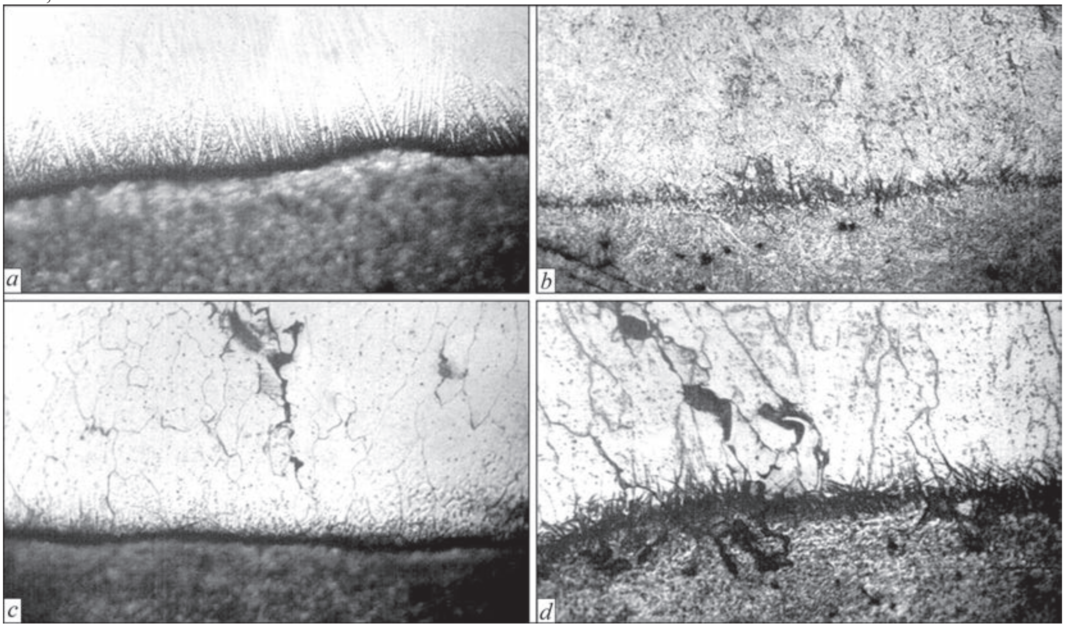

Figure 6. Microstructure (×200) of metal near the fusion line (top) and base metal (bottom) with different boron content, %: *a* — without boron; *b* — 0.007; *c* — 0.02; *4* — 0.04

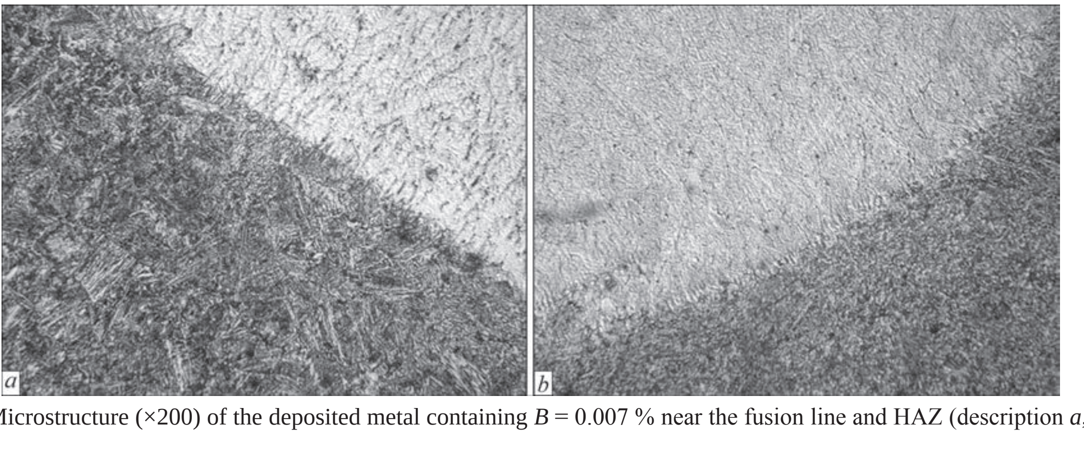

Figure 7. Microstructure (×200) of the deposited metal containing *B* = 0.007 % near the fusion line and HAZ (description *a*, *b* — see in the text)

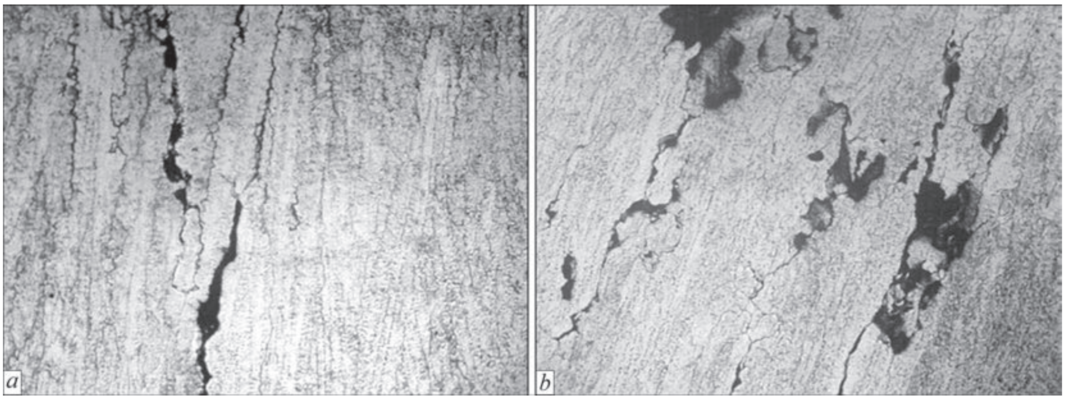

Figure 8. Microstructure (×200) of regions of a central part of the deposited metal with the boron content: *a* — 0.02 %; *b* — 0.04

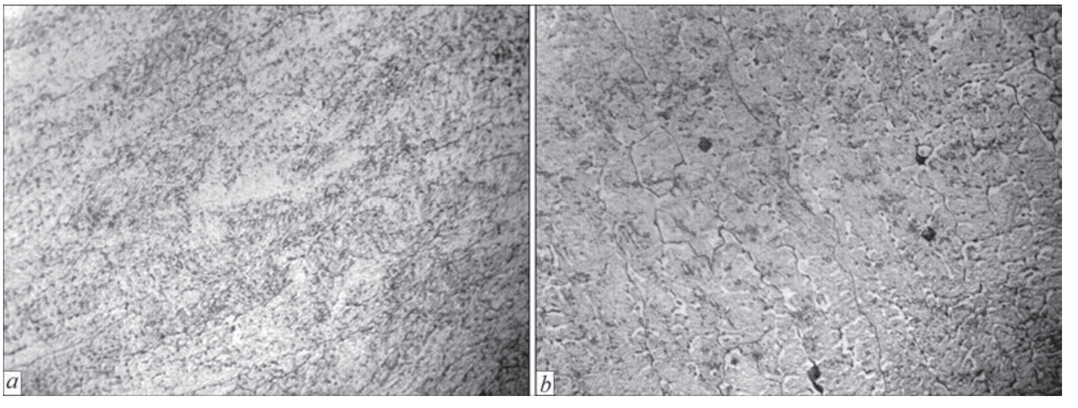

Figure 9. Microstructure (×200) of the upper part of the deposited metal in the specimens with the boron content: *a* — 0.02 %; *b* — 0.04

the deposited metal in the amount of up to 0.04 % leads to refinement of the microstructure of metal and reduction in the average grain size by 2.2–2.5 times.

Microstructure of the matrix is fine acicular martensite (Figure 5). In the specimens, microalloyed by boron, in the lower part of the deposited metal, closer to the fusion line, separate regions with coarser needles are observed (needles up to 50 μm) (Figure 6, *b*–*d*), the hardness of these regions is the same as the hardness of other zones of the deposited metal.

In the boundaries of crystallites in the structure of all studied specimens, smooth light precipitates are observed, which probably represent an alloyed austenite. The hardness of these precipitates amounts to *HV*1 — 6340–6420 MPa. Specimen No. 2 has the smallest number of such precipitates, and the specimen No. 4 has the largest one.

The structure of HAZ in the specimen No. 2 (0.007 % B) on the overheating area represents ferrite and pearlite (Figure 7, *a*). In HAZ some sections are observed, where the overheating area is absent, and on the side of base metal, the dispersion region of recrystallization is observed with fine-grained ferrite-pearlite structure (Figure 7, *b*), the metal hardness of which amounts to *HV*1 2380–2450 MPa. This structure is formed during repeated heating in the process of successive deposition of beads.

Defects on the fusion line and in HAZ in the specimens No. 1 (without B) and No. 2 (0.007 % B) were not detected. In the specimens Nos 3, 4 near the fusion line, a large number of microcracks was noted (Figure 6, *c*, *d*), which mostly pass along the boundaries of grains and propagate further into the deposited metal. As the boron content increases, a number of cracks and their size grow (Figure 8). The presence of precipitates of rounded shape in the body of crystallites also should be noted, which are probably complex carboborides. A number of these precipitates also grows with an increase in the boron additive content in the deposited metal (Figure 9).

Table 2. Microhardness of areas of metal, deposited using experimental flux-cored wires with different boron content

Area of deposited metal	Microhardness (*HV*1) with boron content:			
	– (Specimen No. 1)	0.007 % (Specimen No. 2)	0.02 % (Specimen No. 3)	0.04 % (Specimen No. 4)
Top	5720–6420	6130–6420	6420–7240	6490–7240
Center	5420–6420	5720–6490	5920–6630	6060–6420
Bottom	5660–5720	5480–5720	6060–6420	6130–7070

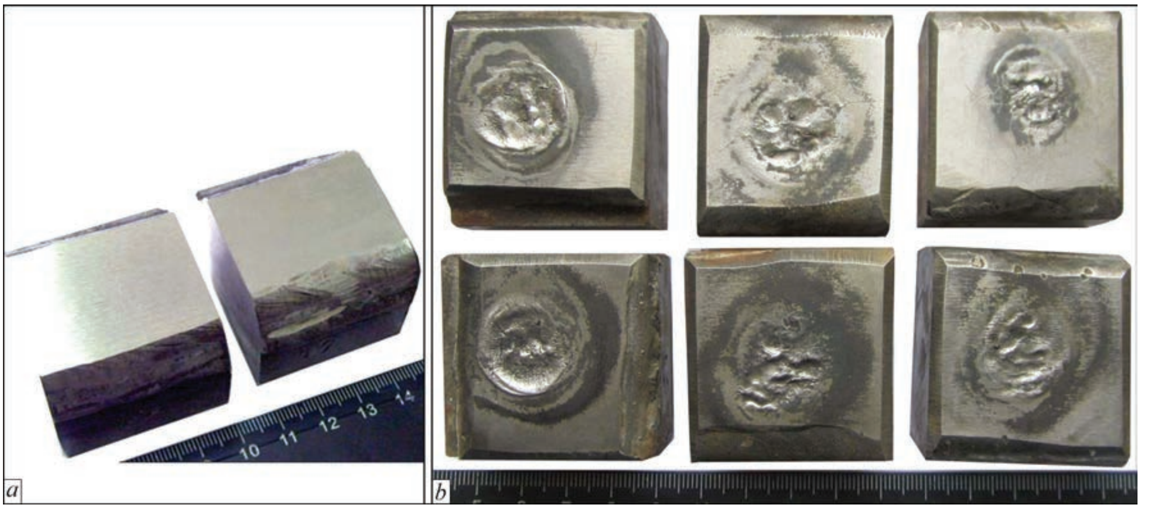

Figure 10. Appearance of the specimens for studying heat resistance of the deposited metal before (*a*) and after tests (*b*)

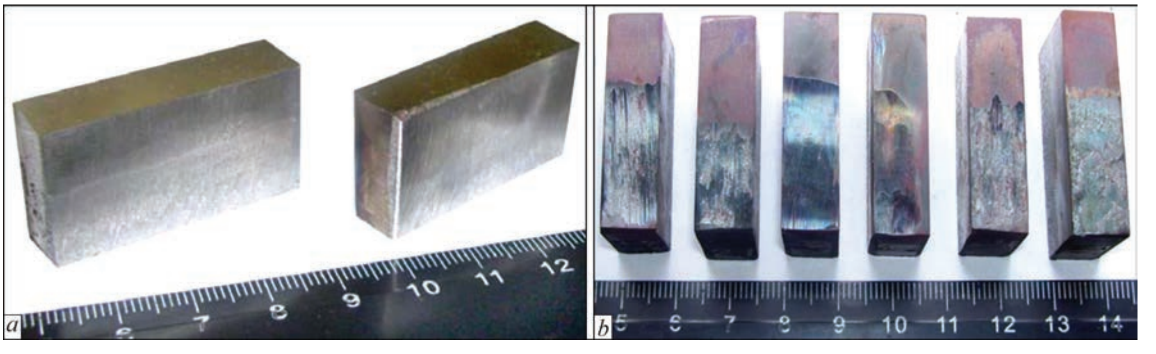

Figure 11. Appearance of the specimens for studying wear resistance of the deposited metal at elevated temperature before (*a*) and after tests (*b*)

An increase in the boron content in the deposited metal from 0.02 to 0.04 % leads to some increase in the microhardness of its matrix all over the volume of the deposited metal (Table 2).

Thus, microalloying of the deposited metal of the type of steel 25Kh5FMS by boron in the amount of 0.007–0.04 % leads to a significant refinement of the microstructure of the deposited metal and an increase in the microhardness of its matrix. At the same time, when the content of boron in the deposited metal is ≥ 0.02 %, microcracks begin to appear in it, which propagate from the fusion line with the base metal and pass through all the layers of the deposited metal. As the boron content grows to 0.04 %, a number and the branching of these cracks increases significantly.

Taken the abovementioned into account, while studying the impact of boron microalloying on the operational properties of the deposited metal, it was decided to limit the maximum boron content in the deposited metal at the level of 0.01 % to avoid cracking and reduce the operational properties of the deposited metal.

Surfacing of the specimens to determine thermal fatigue resistance was performed by single beads with overlapping of 40–50 % on the workpieces with the sizes 20×40×200 mm. For the manufacture of specimens to study the resistance of the deposited metal under the conditions of friction of metal against metal at elevated temperature, surfacing by single beads without overlapping on the end of the workpieces with the sizes of 15×25×200 mm was performed. Such surfacing technique was chosen based on the sizes and design of the specimens to determine the operational characteristics of the deposited metal according to the developed procedures of experimental studies.

Table 3. Results of studying heat resistance of the deposited metal (average values)

Specimen number	Number of cycles before appearance				Depth of cracks, mm	
	Of first crack	Of new cracks	Fine network of cracks	Propagated network of cracks	Medium	Maximum
1	70	100	140	175	0.07	0.13
2	100	130	170	200	0.04	0.07

Table 4. Results of studying wear resistance at elevated temperatures (average values)

Specimen number	Loss of mass, g	
	Of deposited specimen	Of ring (counterbody)
1	0.456	5.4
2	0.373	2.8

The specimens for studying thermal stability of the deposited metal had the sizes of 40×40×30 mm. Moreover, the heated surface had the sizes of 40×40 mm. The specimens for studying wear resistance at elevated temperatures had the sizes of 10×17×40 mm. Moreover, a wear surface had the sizes of 10×17 mm. The appearance of the specimens before and after studies of heat resistance and wear resistance is shown in Figures 10 and 11, and the results of these studies are presented in Tables 3 and 4, respectively.

Microalloying of the deposited metal 25Kh5MFS by boron in the range of 0.007–0.01 % has a positive effect on heat resistance of the deposited metal of the type 25Kh5FMS. Thermal fatigue cracks in the metal of the deposited specimen microalloyed by boron, are initiated later, their average length and number is smaller than in the reference specimen. Also the positive effect of boron microalloying on wear resistance of metal in friction of metal against metal at elevated temperatures was noted — losses of weight of the specimen and the ring (counterbody), which wears out the specimen, decrease by 1.2 and 2.0 times respectively.

CONCLUSIONS

1. Microalloying of the deposited metal of the type 25Kh5FMS by boron in the range of 0.007–0.01 % leads to a significant refinement of its microstructure and some increase in the microhardness of its matrix. In this case, an increase in the boron content in the deposited metal being ≥ 0.02 % leads to the formation of a large number of crystallization cracks in it, that propagate through all the layers of the deposited metal.

2. Microalloloying of the deposited metal 25Kh5MFS by boron in an amount of 0.007–0.01 % increases its heat resistance and wear resistance at elevated temperatures by 1.4–1.75 and 1.2–2.0 times, respectively, which can be explained mainly by refinement of its microstructure and an increase in the microhardness of its matrix.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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