Modification of the surface of steel 3Kh2V8F by application B-Al-coatings by methods of thermal-chemical treatment and electron-beam processing

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Abstract. The development of new protective coatings is of great fundamental and applied importance for increasing operational properties of surface layers in machine parts, increasing their durability and expanding their functionality. The study is devoted to the creation of coatings based on boron and aluminum on the surface of alloyed steel using a method, combining diffusion saturation (DS) and subsequent electron beam processing (EBP). DS was carried out in saturating pastes based on boron carbide and aluminum at temperature of 1050 °C for 2 hours. As a result of processing, a diffusion layer with thickness of up to $(5.6–5.8) \times 10^2 \mu m$ and complex structure with depth-heterogeneous composition was formed on the steel surface. The subsequent EBP led to a complete transformation of the primary diffusion layer and an increase in its thickness to $10^3 \mu m$. XRD analysis showed significant differences in composition before and after EBP: after EBP tungsten borides $(WB, W_2B_9)$ and iron $(Fe_2B)$ were detected. In addition, it was determined that the distribution of microhardness and elemental composition $(B, Al, W)$ over the depth of the layer after EBP have a more favorable profile without significant fluctuations compared to the sample after DS.

1. Introduction

Currently alloyed and special steels are selected for the production of parts operating under conditions of high mechanical and thermal stresses, accompanied by shock loads. Often the surface layers of these steels need additional hardening due to high mechanical and thermal loads. Thus, it is known that during injection molding, more than 80% of all dies fail due to the formation of surface cracks caused by thermal stresses [1]. Thus, one of the important challenges in mechanical engineering is the development of methods for improving functional properties of surface layers by various hardening methods.

Improving functional properties of parts made of tool steels can be provided by thermal-chemical treatment (TCT). TCT is of particular interest due to its ability to provide enhanced physical and mechanical properties at low costs. For example, boriding provides a number of positive properties, such as high hardness, low coefficient of friction, high wear resistance, resistance to erosion, corrosion and oxidation [2]. At present, in mechanical engineering technology, when modifying the surface layers of steels and alloys, it is possible to efficiently use multicomponent TCT, which comprises of
simultaneous or sequential diffusion saturation of the surface of metals and alloys with several chemical elements. Such complex TCT methods as boroaluminizing can significantly increase wear resistance, as well as increase oxidation resistance at high temperatures, corrosion resistance and other properties of the surface layers of machine parts [3].

2. Identifying the problem
Despite a significant number of scientific and technical publications, the problem of finding effective methods of hardening remains relevant. Today, the task of developing a theory applicable to the formation of boroaluminized coatings having a set of physic-mechanical properties — high wear, heat and corrosion resistance — is still not carried out. Conventional boroaluminizing leads to the formation of a layer in which the phases, arranged in layers, do not allow the positive properties of the boroaluminized layer to fully manifest themselves. Existing methods for creating protective coatings usually involve the use - as a basis - of low-cost carbon structural steels subjected to surface modification: the economic effect is achieved by replacing expensive alloy steels and alloys. However, this approach has several limitations:

1. The boron-based coatings obtained by diffusion methods have several disadvantages: the layered structure of the coating, high brittleness, a sharp difference in properties during the transition from the coating to the substrate, the multidirectional nature of the distribution of residual stresses due to the anisotropy of the thermal expansion of boride phases.
2. For tools, working under pressure and under conditions of shock loads and elevated temperatures, there remains a need to ensure strength and high mechanical properties not only on the surface, but also inside their volume. Carbon steels often cannot provide this condition.

In this regard, it is particularly promising to study methods for creating composite structures on the surface of alloyed steels based on boron and aluminum so that both solid and plastic phases are located in the coating in various combinations (ordered or random). It is known that electron beam processing (EBP) of boronized layers leads to phase redistribution and significant microstructural changes [4]. So, as a result of processing, a Fe3B phase is formed in addition to the existing FeB and Fe2B. Moreover, instead of the “classic” needle boronized coating, coatings with a composite structure are obtained. In [5] it was established that the wear resistance and ductility of this type of coating is higher than that of the needle layer. Thus, the use of EBP is an effective method of leveling the high fragility of boron-based coatings due to the formation of coatings with a composite structure. This is achieved by phase transformation as a result of the surface layers being re-melted under the influence of an electron beam, which provides a smoother distribution of microhardness, a favorable distribution of residual stresses and improved adhesion properties [6].

The purpose of this work is to obtain a coating with a composite structure to increase the complex of mechanical properties of the surface of 3Kh2V8F steel using the combined method of thermal-chemical and electron-beam treatment.

3. Materials and methods
The coatings were synthesized on the surface of 3Kh2V8F die tool steel in two stages:

1. First, the process of diffusion boroaluminizing was carried out in pastes containing powders of boron carbide, aluminum, and sodium fluoride as an activator. The methodology for the preparation of pastes and the composition of the powder mixture are described in [7, 8].
2. The second stage involved additional treating the obtained diffusion coatings with an electron beam in an electron-beam installation with an EPA-60-04.2 electron gun with a BUEL control unit and a high-voltage rectifier [9]. Heating was carried out by a continuous beam for 2-5 minutes at specific density of W = 5.7 × 10^2 W/mm². The residual pressure in the vacuum chamber did not exceed 2 × 10⁻³ Pa.

The microstructure of the samples was studied using a METAM RV-34 metallographic microscope. Microhardness was determined on a PMT-3M microhardness tester with a load of 0.5 N. X-ray microanalysis was carried out on a JSM-6510LV, JEOL scanning electron microscope with an INCA Energy 350, Oxford Instruments microanalyzer. The phase composition was determined on Phaser 2D, Bruker X-ray diffractometer in copper radiation in an angular interval of 10 ° - 90 ° 2θ.
The studies were carried out at East Siberia State University of Technology and Management (Science Center “Progress”; Department of Mechanical Engineering Technology, Metal Working Machines and Complexes; Department of Metallurgy and Metal Processing Technology) and Institute of Physical Material Science of the Siberian Branch of the Russian Academy of Science (Physical Material Science laboratory).

4. Discussion

As a result of DS, a coating with thickness of up to \((5.6–5.8) \times 10^2\) μm with a complex structure is formed on the steel surface, as shown Figure 1 (a). Depending on the depth, several structural zones in the coating can be distinguished. Porous outer zone 1 consists of large light crystals oriented in the \{001\} direction. Zone 2 is located below and is characterized by the presence of small or elongated crystals located in the light matrix. Zones 3 and 4 have a cellular structure: the first is with predominant light phases, the latter is with dark, apparently ferritic crystals.

The subsequent EBP led to a complete transformation of the primary diffusion layer and an increase in its thickness to about \(10^3\) μm, as shown in Figure 1 (b). A homogeneous layer with no visible signs of zoning (layering) was obtained. On the surface of the layer dendritic formations are found.

![Figure 1. The microstructure of steel 3Kh2V8F: (a) - after DS; (b) after combined treatment.](image)

XRD analysis revealed the presence of FeB, Fe₃Al, Fe₇W₆, Fe₂O₃ (Figure 2). The presence of iron boride and aluminide is natural for DS in pastes based on boron carbide [7, 8]. The presence of ferrovanadium is unlikely. According to the Fe – W phase diagram, the region of existence of the Fe₇W₆ phase is in the temperature range 1190–1637 °C [10]. The DS process was carried out in a furnace without controlled atmosphere; therefore, the presence of iron oxide can be explained by the diffusion of atmospheric oxygen through the paste.
The electron beam treatment of the diffusion layer led to the formation of vanadium (WB, W₂B₉) and iron (Fe₂B) borides (Figure 3). In this case, FeB boride was not detected. Of the carbide phases, complex carbide Fe₃W₃C-Fe₄W₂C was revealed. The distribution of microhardness over the depth of the layer showed that the sample after EBP has a more favorable profile without significant fluctuations compared to the sample after MD (Figure 4). The element distribution of boron, aluminum, and tungsten over the depth of the layer after EBP is more uniform compared to the profile after DS (Figure 5, 6).

Figure 2. X-ray powder diffraction analysis of steel 3Kh2V8F after DS

Figure 3. XRD analysis of steel 3Kh2V8F after combined treatment.
Figure 4. Microhardness distribution of 3Kh2V8F steel after DS (TCT) and combined treatment (EBP).

Figure 5. Microstructures of steel 3Kh2V8F with set of spectra lines: (a) after TCT; (b) after combined treatment.
Figure 6. Distribution of elements (B, Al, W) by layer thickness: (a, b, c) - after TCT; (d, e, f) - after combined processing.

Figure 7. Microstructures of steel 3Kh2V8F, ×1500: (a) – after TCT; (b) – after combined treatment.

SEM images showed that the solid phases - borides and iron carbides differ depending on the treatment by their structure and size (Figure 7).
5. Conclusion
The combined processing method results in equalization of the phase composition along the depth of the layer and obtaining a structure with a uniform composition. Lamination and phase heterogeneity along the coating depth are significantly reduced.

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