Features of boriding die steel D5 by electron beams

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Abstract. The microstructure and microhardness of the boride layers formed on die D5 steel by the methods of electron beam borating in vacuum under continuous and impulsive bunch modes are investigated and confronted. Formed layers have a heterogeneous structure, which combines solid and plastic components resulting in the fragility reduction of boride layer.

1. Introduction
The possibility of obtaining the required complex of physical and mechanical properties of products, depending on the conditions of their operation, is one of the most important aims of materials science. Achieving this aim requires the improvement of existing, and sometimes the creation of new materials and processing methods. During operation, the most intense loads are exposed to the surface layers of parts and tools, in connection with which it can be argued that it is the structure and properties of the surface of the part that, as a rule, determine the performance of the product as a whole.

Diffusion saturation of the surface of products with boron protects parts from wear under various operating conditions. In addition, boride layers have increased corrosion and heat resistance. Standard boriding technologies give stable results, but at the same time they have low productivity and require high resource costs. So, for example, in electrolysis and liquid boriding, crucibles have a low resistance in borating melts, the parts must be washed and the effluent must be neutralized. Powder boriding does not allow mechanization and automation of the process, and also has a high cost of the saturating mixture. A common disadvantage of existing borating methods is the process duration, which is at least 6 hours. For this reason, modern studies of the borating process are devoted to its intensification, which will lead to a reduction in processing time and, as a result, to an increase in the productivity of the process. In addition, the high hardness and low plasticity of the boride layer impede the operation of products, especially under dynamic and alternating loads.

The solution to this problem is seen in the creation of borated layers with a heterogeneous dispersed structure consisting of boride inclusions in a relatively plastic solid solution, which are less brittle than the traditional columnar structure of the borated layer [1].

An effective way to reduce brittleness and increase plasticity is the use of electron beam heating. In addition, the layers after electron beam boriding have a heterogeneous structure that combines hard (brittle) and more plastic structural components.

The paper considers the features of surface hardening of die steel D5 under the influence of powerful electron beams due to the formation of layers based on iron borides.

D5 tool die steel is used for the manufacture of complex-shaped products operating at pressures up to 1600 MPa – rolls, sections of body dies, hole-piercing dies for cutting their sheet metal, dies,
knurled dies, punches / dies / die-cut dies, and other products. Table 1 shows the chemical composition of D5 steel in % [2].

| Table 1. Chemical composition of D5 steels (%) |
|-----------------|-----------------|
| Si              | 0.15 – 0.35     |
| Mn              | 0.15 – 0.4      |
| Ni              | 0.35            |
| S               | 0.03            |
| P               | 0.03            |
| Cr              | 11 – 12.5       |
| V               | 0.7 – 0.9       |
| Cu              | 0.3             |
| Fe              | ~84             |

2. Experimental part

2.1. Calculation method

Thermodynamic modeling was performed using the TERRA software package. The program is designed to calculate arbitrary systems with chemical and phase transformations. It allows to simulate a very equilibrium state and implements method and algorithm calculations created in the N.E. Bauman Moscow State Technical University. The program is associated with an extensive database of properties of individual substances, which makes it suitable for the study of arbitrary compositions of chemical composition [3].

A three-dimensional mathematical model of the thermal impact of a powerful fast-moving electron beam on the surface of die steel D5 was built using the COMSOL Multiphysics software complex. When modeling the electron beam processing process using the COMSOL Multiphysics software complex, global parameters were set: power – 400 W, electron beam diameter – 1 mm, the sample was a cylindrical plate with a diameter of 15 mm and a height of 7 mm, coating – amorphous boron.

![Figure 1](image1.png)

**Figure 1.** Temperature distribution after one pass of electron beam over the surface of the simulated sample.

![Figure 2](image2.png)

**Figure 2.** Temperature distribution over the surface and volume of the sample after 60 seconds of electron beam treatment of the sample.
The distribution of the current density over the beam section is close to the Gauss law [3]. In the process of thermal action by concentrated energy flows, the temperature in the thin surface layer of the metal reaches values of the order of 2000 – 2500°C, exceeding not only the temperature of phase transformations, but also the melting point of the material, while due to the high heating and cooling rates in the zone of action by an electron beam of the order of $10^4$ – $10^6$ K/s, real melting of the surface may not occur. Figures 1 and 2 show the temperature distribution over the surface and depth of the sample after one pass of electron beam and after 60 seconds of sample processing. As a result of one passage of the electron beam on the surface of the sample, the temperature reached 190°C, after 60 seconds of electron beam processing, the temperature was 830°C.

2.2. Research method

X-ray phase analysis was carried out on a Phaser 2D Bruker diffractometer (Cu Kα - radiation).

Microhardness was measured on a PMT-3M microhardness meter. The microhardness tester is equipped with an adapter with a digital camera and NEXSYS ImageExpert MicroHardness 2 fingerprint image processing software.

Microstructure of transverse thin sections of the samples was examined on a METAM RV-21 metallographic microscope equipped with a VEC-335 digital camera and NEXSYS ImageExpert Pro 3.0 software for quantitative metallographic analysis.

3. Result and discussion

Thermodynamic calculations showed that when using a mixture of amorphous B formed borides of iron, chromium, vanadium and manganese. It can be seen from the calculations that boron actively reacts with the surface of D5 steel (figure 3).

![Figure 3](image-url)

**Figure 3.** The yield of condensed phases in the synthesis of boride on D5 steel (50-50).

As a result of calculations, the ideal conditions for the interaction of amorphous boron with the surface of steel D5 for the formation of a composite coating to a depth of 5-100 microns have been determined.

Electron beam boriding was carried out on the surface of the D5 die steel. Samples were prepared by applying amorphous B on a previously prepared steel surface.
Heating of standards was carried out by an electronic bunch in the pulse-mode with parameters: accelerating tension – \( U = 7 \text{kV} \); current of bunch – \( I = 25 \text{A} \). Treatment was conducted with duration of one impulse – \( t = 20 \mu \text{s} \); amount of impulses – \( N = 1000 \); frequency of the following of impulses of current of bunch – \( f = 3 \text{Hz} \). Pressure in a vacuum chamber is \( 5 \times 10^{-2} \text{ Pa} \) [2, 5-6].

Electronic heating by a continuous bunch during 2-5 minutes at specific power is \((2-2.5) \times 10^4 \text{ W/cm}^2\). Remaining pressure in a vacuum chamber did not exceed \( 2 \times 10^{-3} \text{ Pa} \).

XRD analysis showed that by electron beam boriding with a continuous action, there are peaks of iron boride \( \text{Fe}_2\text{B} \) and iron carbide \( \text{Fe}_3\text{C} \), phases of chromium and vanadium borides (\( \text{Cr}_2\text{B}, \text{VB} \)) are also present (figure 4).

**Figure 4.** X-ray diffraction pattern of a layer based on B formed on D5 steel (continuous beam).

**Figure 5.** X-ray diffraction pattern of a layer based on B formed on D5 steel (pulse-mode).
XRD analysis of layers obtained by a pulsed beam showed more interesting results. There are peaks of iron, chromium and vanadium borides (figure 5). The study shows that boron actively reacts with the surface of D5 steel, and we have obtained many phases of iron, vanadium, chromium borides on the surface of the steel.

Metallographic analysis showed that the surface layers obtained as a result of boriding by different methods differ in structure (figure 6).

Subsequently borating with used a constant electron beam, there is no transition zone; a clear boundary between the layer and the metal is noticeable. It can be seen in the layer that it contains dendrites and eutectics (figure 6 a). The layer obtained by the pulsed beam looks the most homogeneous (figure 6 b). The layer thickness after boriding with a pulsed beam is 15-30 µm, and with a continuous beam it reaches 150-400 µm.

![Figure 6. Structure of layer on the basis of amorphous B on D5 steel: (a – continuous electron beam, ×250, b – impulsive electron beam, ×1000).](image)

When measuring the microhardness of boride layers with a step of 30-50 µm, a different distribution by thickness was found (figure 7). But, in all considered samples, a logical distribution of microhardness was observed, depending on the depth of the layer. Rare fractions reach a hardness of HV ≈ 15000 MPa and are located at the surface of the layer. The layers have a very complex disordered structure. On a sample treated with a pulsed beam, a thinner layer is visible than on a sample treated with a constant beam. This can be explained by the fact that a powerful pulse of electrons from the mixture particles until the sample surface melts. The microhardness of the steel itself increased to HV ≈ 4000-6000 MPa. This clearly indicates the influence of the electron beam on steel hardening.

![Figure 7. Microhardness of the layer on the D5 steel: (a – continuous electron beam, b – pulse-mode).](image)
4. Conclusion
As you know, borides have high hardness, but they have a huge drawback - they are very fragile. An electron beam in a vacuum solves this problem. There is a layer containing particles of hard borides and carbides in a soft eutectic. This significantly reduces the brittleness of the resulting layers.

The results obtained give us grounds to conclude that an electron beam is used to increase the strength of cutting tools, etc., which experience heating during operation to high temperatures without a significant decrease in operational properties.

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