Thermophysical model of electron beam boriding of titanium alloy VT-1

A. E. Lapina[1] ann_lapin@mail.ru

N. N. Smirnyagina[1] smirnyagina09@mail.ru

Institute of Physical Materials Science SB RAS

6 Sakhyanova Str., Ulan-Ude, Republic of Buryatia,670047, Russia

The investigation is aimed at developing a thermophysical model of electron beam boriding of titanium alloy VT-1.

Features of introducing of the focused electron beam into titanium alloy VT-1 were investigated. Modeling of thermophysical processes was carried out using the COMSOL Multiphysics software complex. The stages of constructing a mathematical model of thermal fields arising in the sample during electron beam processing are considered. Numerical calculations made it possible to show that the temperature-time conditions of heating and cooling of the titanium alloy VT-1 affect the nature of structural transformations.

MATHEMATICAL MODEL

The problems of thermal processes arising when exposed to highly concentrated electron flows are based on the solution of the thermal conductivity equation (1):

$$c\rho \frac{\partial T}{\partial t} = -\nabla \boldsymbol{J},\ \boldsymbol{J} = -\boldsymbol{\lambda} \nabla T \qquad (1)$$

where c, ρ, λ – the thermal capacity, density, and heat conductivity depending on temperature and coordinates.

The volumetric heat source can be described by the equation (2):

$$q(x',y',z')=q_0\, e^{[-(x'^2+y'^2)\, k_1 - [(z'-h)]^2\, k_2]} \qquad (2)$$

where q_o - the specific power of the source, k_1 - the coefficient of concentration of the source on the surface of the body, k_2 - coefficient of concentration of the source inside the volume, h - the depth of the maximum energy release, x, y, z – coordinates.

Comsol Multiphysics is a universal software complex based on the finite element method for computer modeling of physical problems.

Modeling the electron beam processing process using the COMSOL Multiphysics:

1. Selects the dimension of the model. A three-dimensional model of the electron-beam exposure process on the sample surface is constructed.
2. The choice of physics and type of research. Using the Deposited Beam Power section of the Heat Transfer in Solids module, the effect of the electron beam on the sample is described (Fig. 1).
3. Defining geometry and global variables.
4. Addition of materials. The initial alloy VT-1 was a mixture of two modifications of titanium α- and β-Ti.
5. Generation of a grid. In the COMSOL Multiphysics environment, the calculation is performed using the finite element method. The mesh selected in the model is triangular mesh size - fine.

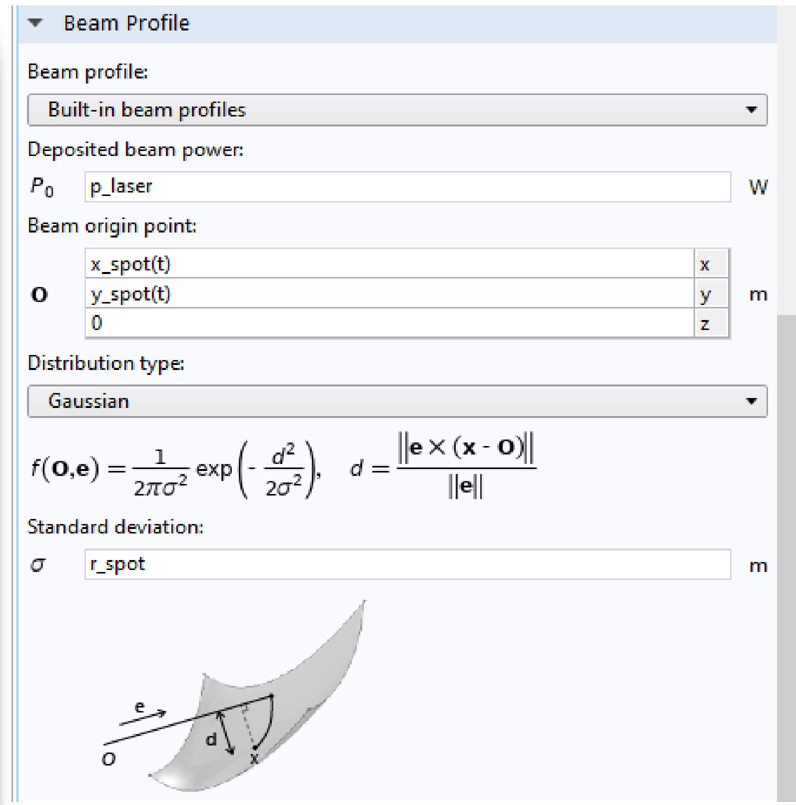


Fig.1. Beam Profile.

To study temperature changes, the thermal conductivity module in solids is used - Heat Transfer in Solids (ht). Electron beam exposure time t = 60 s. The motion of the electron beam along the x and y-axis is specified using the Analytic and Interpolation functions. According to the processing conditions, the electron beam is first focused on the surface of the sample, and then, using the control unit, it is converted into a raster and scans along its entire diameter.

The sample is a cylindrical plate with a diameter of 15 mm and a height of 7 mm (Fig. 2). The power of the electron beam P=200 W. Electron beam diameter 1 mm.

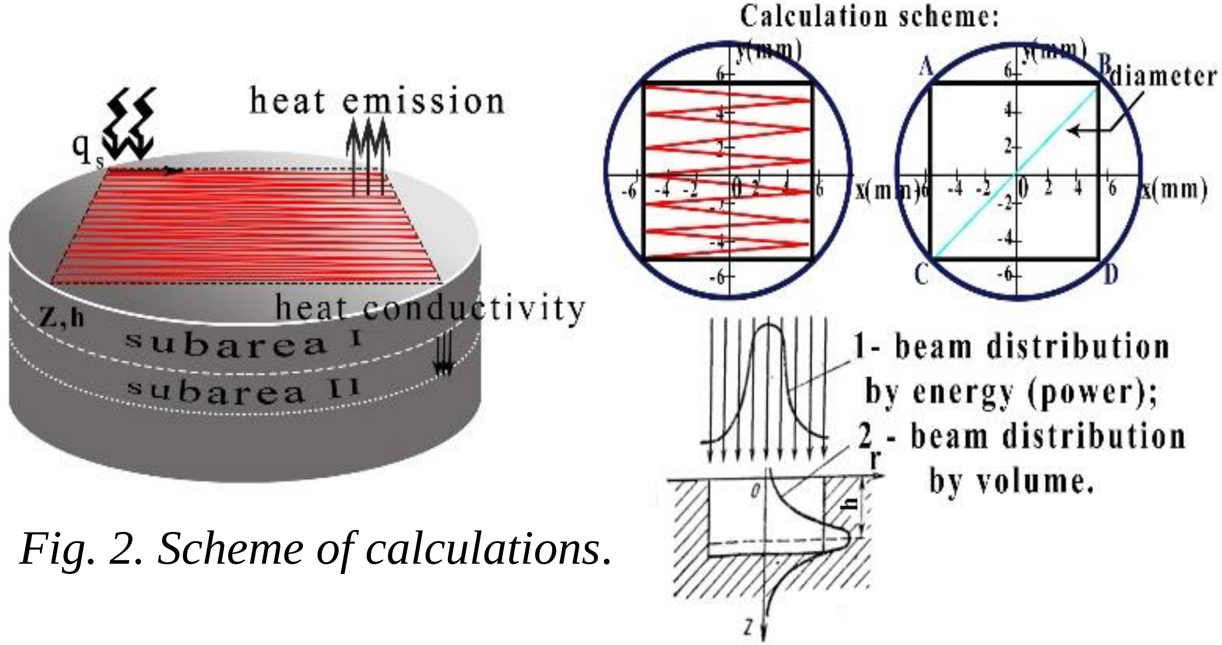


Fig. 2. Scheme of calculations.

RESULTS AND DISCUSSION

The temperature distribution over the surface and deep into the sample in the direction of electron beam motion was determined. As a result of one passage of the electron beam on the surface of the sample, a temperature of 113 °C is reached (Fig.3). Processing of a sample of titanium alloy VT-1 with the help of an electron beam is carried out in scanning mode.

The repeated passage of the beam over the surface leads to an increase in the total temperature of the sample being treated. The scanning frequency is set equal to 50 Hz, the process of electron beam processing is high-speed.

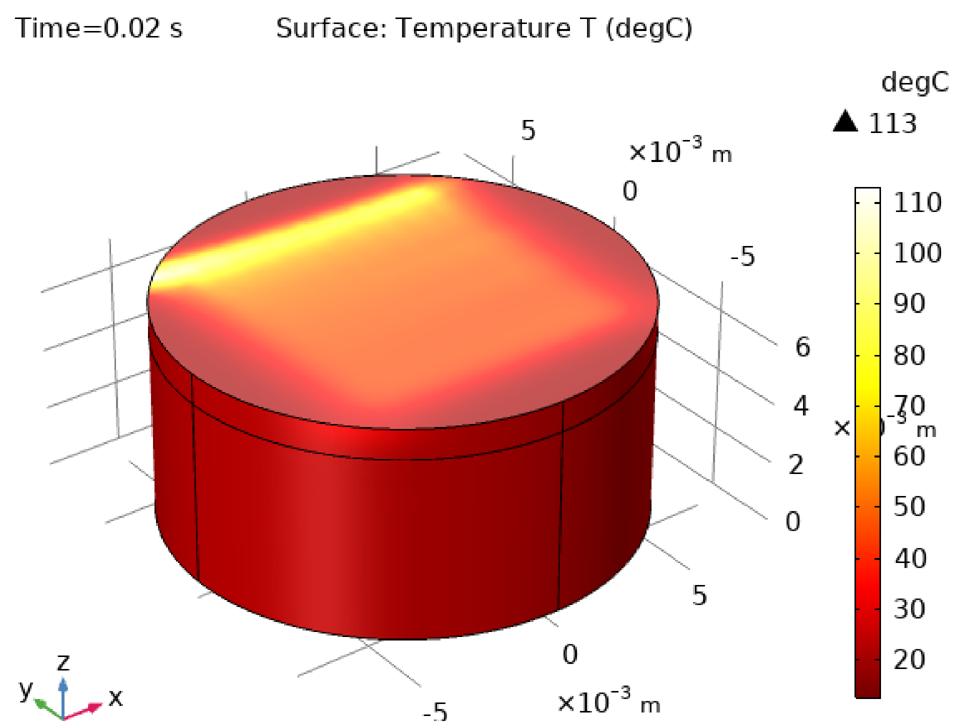
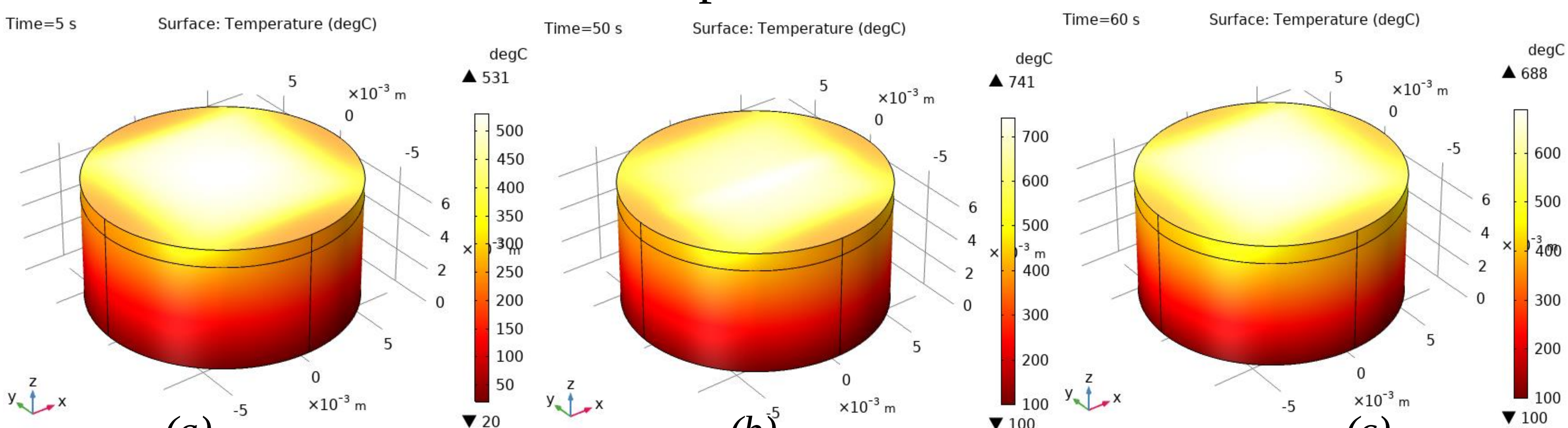


Fig. 3. Temperature distribution after one pass of the electron beam over the surface of the sample.

After 5 seconds after the start of the treatment process, the maximum temperature reaches 531 ^{o}C, after 50 seconds the sample surface is heated to 740 ^{o}C, the bottom surface of the sample remains cold. After completion of the electron beam processing process, the temperature is 688 °C. Maximum temperatures are reached on the surface in the central part of the sample, which is associated with the trajectory of the electron beam. At the same time, temperatures in the heat exposure zone can reach 2000-2500 ^{o}C, which indicates high heating and cooling rates in the electron beam exposure zone of the order of 10^6.



(a) *(b)* *(c)*

Fig. 4. Temperature distribution over the surface and volume of the sample after: 5 seconds of electron-beam processing (a), 50 seconds of electron-beam processing (b) and after processing of the sample with an electron beam (c).

EXPERIMENTAL

For the experiment, samples made of titanium alloy VT-1 in the form of square plates of 15x15 mm and a height of 7 mm were selected. Layers of saturating or reaction coatings were formed. The saturating coatings contained a borating component and an organic binder. The reaction coatings included stoichiometric mixtures of TiO_2 oxide, boron, carbon, and an organic binder. A 1:10 solution of BF-6 adhesive in acetone was used as the organic binder.

Electron beam processing was carried out in a vacuum at most 2×10^{-3}Pa at power electron beam W = 250-450 W for 1-3 min.

Fig. 5. General view of electron beam installation

The microstructure of the transverse sections of the samples was studied using a METAM PB-21 metallographic microscope. Was formed composite layers with a thickness of 80-100 μm. The structure of the layers is eutectic.

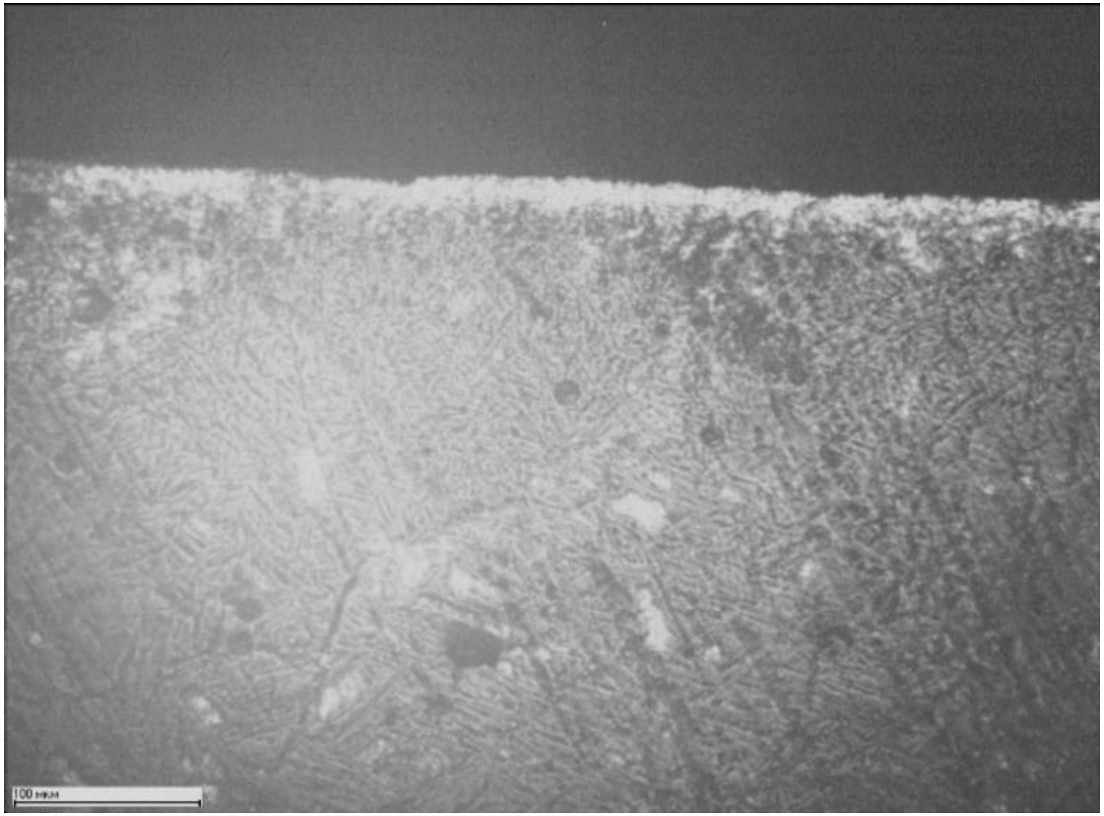


Fig. 6. Structure of boriding layer on alloy VT-1 from saturating coating of boron carbide B_4C.

Solid-phase boriding from saturated coatings of amorphous boron.

The presence of α-Ti with large hexagonal cell parameters and a large amount of titanium boride was detected radiographically TiB (PDF 01-073-2148). There are no β-Ti reflexes, which indicates high temperatures on the surface of the titanium alloy during electron beam boriding. There is a significant thickness of the modified layer (more than 700-900 μm).

Solid-phase boriding from saturating coatings of boron carbide.

Figure 6 shows the X-ray pattern of the VT-1 alloy sample after an electron beam boriding from boron carbide-based saturating coatings. The presence of the following phases can be recorded: boron carbide B_4C, titanium diboride TiB2, titanium boride TiB, titanium carbide TiC. The metal base is a mixture of α- and β-Ti. The crystalline phases have a weight of 67.4% and amorphous phases 32.6%.

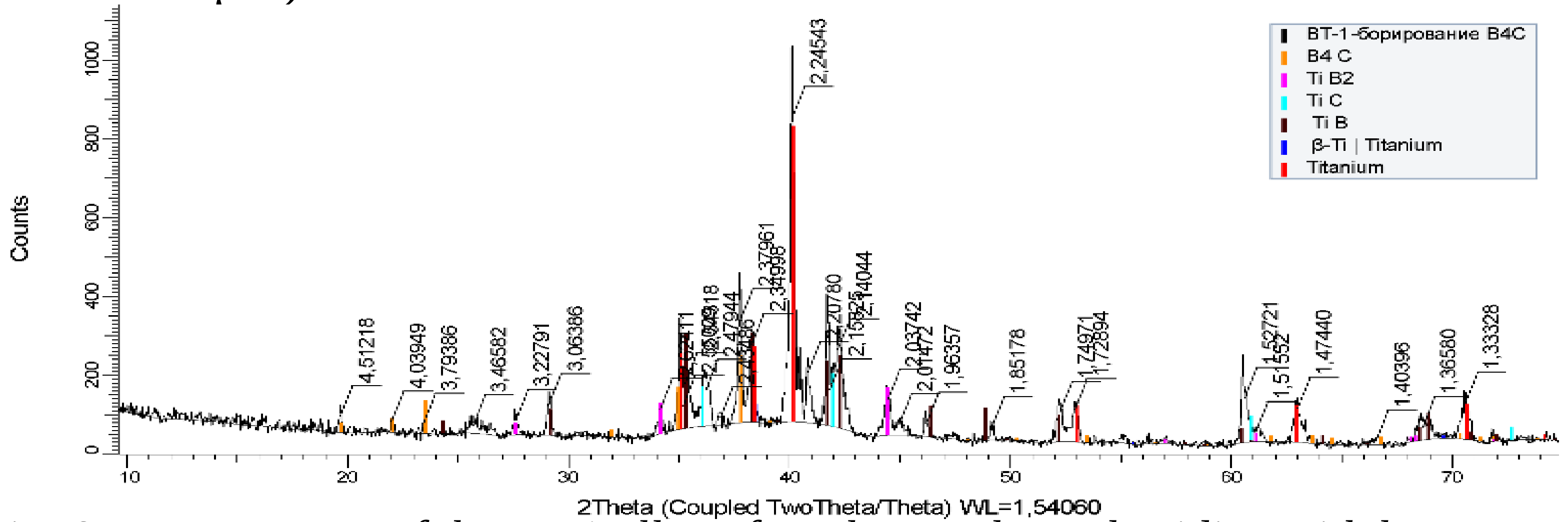


Fig. 6. X-ray pattern of the VT-1 alloy after electron beam boriding with boron carbide

CONCLUSION

As a result of computer modeling, a three-dimensional model of temperature change was built in the Comsol Multiphysics environment due to the effect of a moving focused electron beam source. Peculiarities of electron beam introduction into titanium alloy VT-1 are considered.

Based on numerical calculations of temperature fields, it is shown that the temperature-time conditions of heating and cooling determine the nature of structural transformations. Microstructures were investigated and X-ray phase analysis of boride layers formed at diffusion saturation with amorphous boron and boron carbide at electron-beam boriding in vacuum was carried out.

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Thank you for your attention!