Surface structure of commercially pure VT1-0 titanium irradiated by an intense pulsed electron beam

Yu F Ivanov[1, 2, 3]**, A D Teresov**[1]**, E A Petrikova**[1, 2]**, O V Ivanova**[4]**, I A Ikonnikova**[4]

[1] Institute of High Current Electronics SB RAS, Tomsk, 634055, Russia
[2] National Research Tomsk State University, Tomsk, 634050, Russia
[3] National Research Tomsk Polytechnic University, Tomsk, 634050, Russia
[4] Tomsk State University of Architecture and Building, Tomsk, 634002, Russia

E-mail: yufi55@mail.ru

Abstract. It is shown that pulsed electron beam irradiation of commercially pure titanium at a beam energy density of 10 J/cm^2, pulse duration of 150 μs, number of pulses of N = 5 pulses, and pulse repetition frequency of 0.3 Hz with attendant polymorphic α→β→α transformations allows a more than five-fold decrease in the grain and subgrain sizes of the material structure.

1. Introduction

Electron beams are widely used for vacuum treatment of materials, including their welding, melting, and annealing, as well as for modification of polymers, curing of lacquer coatings, sterilization of foodstuff and medical tools, microwave generation, and excitation of active media in gas lasers [1–4]. The technology of surface modification by intense pulsed electron beams holds much promise due to the possibility of increasing the wear resistance of materials, their corrosion or oxidation resistance, fatigue life, etc. [5–7].

The aim of the present study is to analyze the structure and properties of surface layers in commercially pure titanium irradiated by a submillisecond intense pulsed electron beam.

2. Materials and methods of study

The material under study was commercially pure VT1-0 titanium [8], hereinafter also titanium or Ti, shaped as plates of dimensions 15 × 15 mm and thickness 4.5 mm. Before electron beam irradiation, the specimens were mechanically polished to Ra = 0.02 μm. The specimen surface was irradiated on a SOLO setup by a submillisecond intense pulsed electron beam at a beam energy density of (10–25) J/cm^2, pulse duration of 100 μs and 150 μs, and pulse repetition frequency of 0.3 Hz; the number of pulses was N = 5. The surface structure of the irradiated specimens was examined by optical, scanning, and transmission electron microscopy.

3. Model

In the model proposed, the problem of finding the temperature field in a certain range of electron energy density is reduced to solving the heat conduction equation for the one-dimensional case of heating and cooling of a plate of thickness *d*. The coordinate system is such that the axis x is directed

deep into (inward) the specimen. At $x = 0$, a heat flux is specified, and the backside of the plate is free from heat exchange. In the coordinate form, the heat conduction equation is written as

$$c\rho\frac{\partial T}{\partial t} = \lambda\frac{\partial^2 T}{\partial x^2}.$$

(1)

Here c is the specific heat capacity, ρ is the density, and λ is the heat conductivity of a material.

The boundary conditions for pulsed electron beam treatment have the form

$$-\lambda\frac{\partial T}{\partial x} = q(t)$$

,

(2)

where the heat flux from the surface deep into the specimen is

$$q(t) = \begin{cases} q_0, & 0 < t \le t_0; \\ 0, & t > t_0. \end{cases}$$

(3)

Here q_0 is the average heat flux during the time of electron beam action t_0. The initial temperature is $T(0, x) = T_0$ throughout the specimen depth $0 < x < d$.

For numerical solution of the problem, we use a difference grid with time and space steps τ and h: $t_j = j\tau$ and $x_i = ih$, where j is the number of a time step and i is the number of a space step. The temperature is determined at the grid nodes. The differential heat conduction equation is approximated with the first order in time and second order in space by an explicit scheme:

$$T_{j+1,i} = T_{j,i} + \frac{\tau(T_{j,i+1} - 2T_{j,i} + T_{j,i-1})}{c\rho h^2}.$$

(4)

The numerical solution of the heat conduction equation was used to calculate the temperature fields in Ti specimens irradiated by an intense electron beam with an energy density of (10–40) J/cm^2 and pulse duration of (50, 100, 150, 200) μs. The surface layer thickness was $d = 10^{-3}$ m; the observation time was 300 μs.

For melting and evaporation of the material, we used the following model representation [5]. As the melting temperature T_{mel} is reached in a cell, the cell temperature is taken to be fixed and equal to this melting temperature, and the overall heat

$$q = \frac{(T_{j,i} - T_{nn})c}{q_{nn}},$$

(5)

where T_{ji} is the cell temperature, is expended in melting the specimen; $q = 1$ means that the material transform into a liquid state. The model representation of crystallization is the same, except that q is decreased from 1 to 0, and so is the model representation of evaporation and condensation. As the boiling temperature T_{boil} is reached in a cell, the cell temperature is taken to be fixed and equal to this boiling temperature, and the overall heat

$$q = \frac{(T_{j,i} - T_{\kappa un})c}{q_{\kappa un}}$$

(6)

is expended in evaporating the matter; $q = 1$ means that the matter transforms into vapor.

The thermophysical properties of titanium in calculations were the following [9, 10]: heat conductivity $\lambda = 20*10^{-2}$ W/(cm·K) and specific heat capacity $c_p = 684*10^{-3}$ J/(g·K) both at T = 1000 K; density $\rho = 4.5$ g/cm^3; melting temperature $T_{\text{mel}} = 1881$ K; evaporation temperature $T_{\text{ev}} = 3560$ K; melting heat $q_{\text{mel}} = 358$ kJ/kg; and evaporation heat $q_{\text{ev}} = 9720$ kJ/kg.

Table 1 presents calculated and experimental values of the melted layer thickness for VT1-0 titanium subjected to pulsed electron beam irradiation.

It is clearly seen that the calculation and experimental data on the melted Ti layer thickness are in good qualitative and quantitative agreement. This suggests that the model representation adequately reflects the processes occurring in the Ti surface layer subjected to intense pulsed electron beam irradiation and can be used for interpretation of experimental data.

Table 1. Calculated and experimental thickness of the melted Ti surface layer subjected to intense electron beam irradiation at a pulse duration of 50 μs

| Calculation		Experiment	
E_s, J/cm^2	d, μm	E_s, J/cm^2	d, μm
10	0.0	12	0.5
15	7	18	6
20	13	20	8.5
25	17	25	14

Figure 1 shows calculated dependences of the melted Ti layer thickness on the beam energy density. Analysis of these data allows the conclusion that with a beam energy density of 10 J/cm^2, the surface layer of VT1-0 titanium is involved in solid phase transformations at both pulse durations (100 and 150 μs). The initial stage of surface melting (melted layer thickness ≈ 1.5 μm) is observed at a pulse duration of 100 μs with a beam energy density of 15 J/cm^2 and at a pulse duration of 150 μs with a beam energy density of 20 J/cm^2.
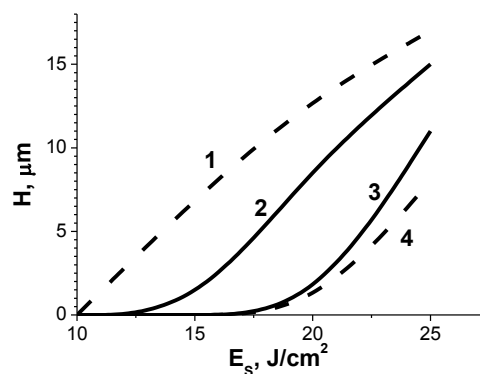

Figure 1. Melted Ti layer thickness vs the beam energy density at a pulse duration of 50 (*1*), 100 (*2*), 150 (*3*), and 200 μs (*4*).

Figure 2 shows calculated dependences of the melt lifetime vs the pulse duration and beam energy density. It is clearly seen that the melt lifetime reaches its maximum (slightly more than 96 μs) at a pulse duration of 100 μs and beam energy density of 25 J/cm^2.

According to the calculations performed, the maximum temperature on the surface of commercially pure VT1-0 titanium varies in the range 1760–4000 K at a pulse duration of 100 μs and in the range 1500–3300 K at a pulse duration of 150 μs. Remind that the beam energy density in both cases was varied from 10 to 25 J/cm^2 (Fig. 3).
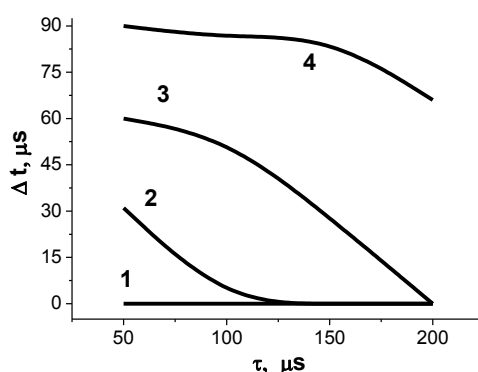
Figure 2. Melt lifetime on the Ti surface vs the pulse duration at a beam energy density of 10 (*1*), 15 (*2*), 20 (*3*), and 25 J/cm^2 (*4*).
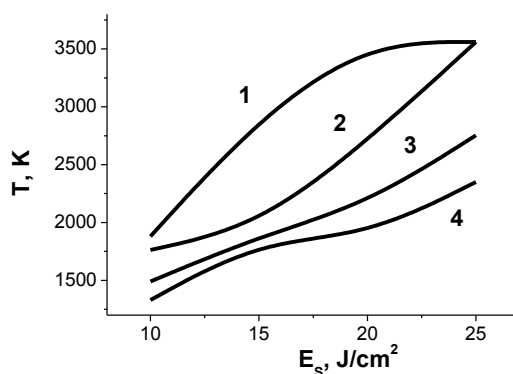

Figure 3. Maximum temperature on the Ti surface vs the beam energy density at a pulse duration of 50 (*1*), 100 (*2*), 150 (*3*), and 200 μs (*4*).

Thus, the calculations suggest that the model adequately describes the thermal processes occurring in the surface layer of commercially pure VT1-0 titanium irradiated by an intense pulsed electron beam and allows one to estimate different parameters the main of which are presented in Figs. 1–3.

4. Experimental results and their discussion

Figure 4 shows images of the surface structure in commercially pure VT1-0 titanium before and after intense electron beam irradiation.

It is readily seen that the initial titanium represents a polycrystalline material with an average grain size of 26 μm (Fig. 4, a). After intense electron beam irradiation, the structure of its surface layer is considerably refined (Fig. 4, b–d). The average grain size revealed on the irradiated surface by optical microscopy is 4–5 μm (Fig. 4, b), 8–10 μm (Fig. 4, c), and 12–13 μm (Fig. 4, d). Hence, the polymorphic α→β→α transformations involved in pulsed electron beam irradiation at 10 J/cm^2, 150 μs, N = 5 pulses, and 0.3 Hz allows a many-fold decrease in the grain and subgrain sizes of the Ti structure. Electron beam irradiation at 15 J/cm^2, 100 μs, N = 5 pulses, 0.3 Hz with attendant melting of the surface layer and its high-rate crystallization provides the formation of a structure in which the minimum average grain size is 8–10 μm (Fig. 4, c).
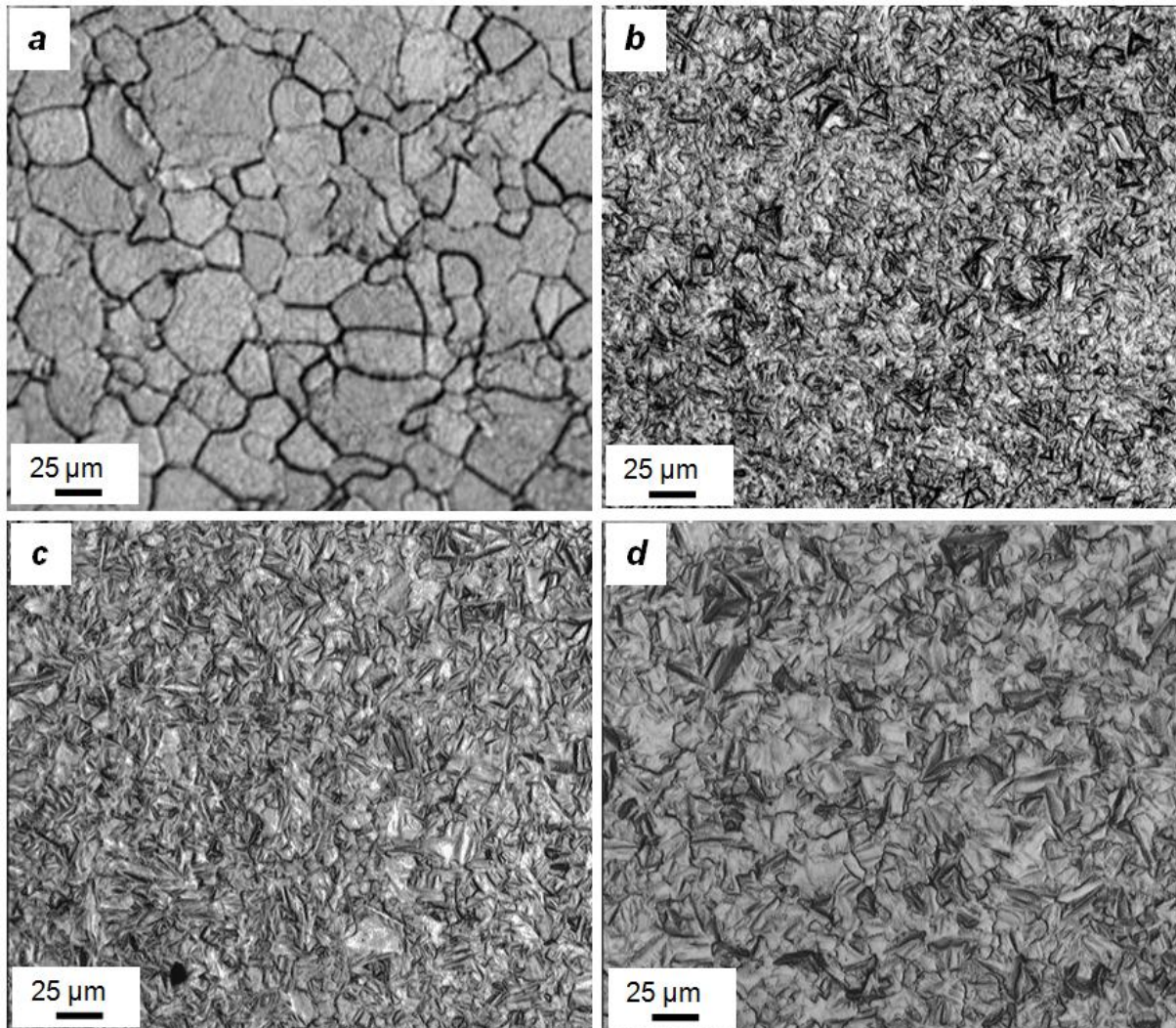
Figure 4. Etched surface of the initial titanium (a) and its surface after electron beam irradiation at 150 μs, 10 J/cm^2 (b); 100 μs, 15 J/cm^2 (c); and 150 μs, 20 J/cm^2 (d).

5. Conclusion

Thus, the one-dimensional model used in the study allowed us to calculate the temperature field arising in commercially pure VT1-0 titanium irradiated by an intense pulsed electron beam. The calculation results were compared with experimental data on the structural phase state of the material subjected to electron beam irradiation at different beam energy densities and different pulse durations. It is shown that pulsed electron beam irradiation at 10 J/cm^2, 150 μs, N = 5 pulses, and 0.3 Hz with attendant polymorphic α→β→α transformations allows a many-fold decrease in the grain and subgrain sizes of the material structure.

Acknowledgement

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