Temperature Field Simulation and SEM Investigation of $\alpha + \beta$ Titanium Alloys Irradiated by Pulsed Electron and Ion Beams[1]

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Abstract – The experiments carried out on pulsed melting of titanium $\alpha + \beta$ alloys of VT6, VT8, and VT9 type were an attempt of significant enlargement of range of irradiation modes and related to these modes parameters of temperature fields induced in the material when irradiated. Enlargement of range of irradiation modes has been attained with employment of three unique wide-aperture sources of pulsed electron and ion beams. Two electron beams of "GEZA" and "RITM" developed in the Institute of Electrophysical Apparatus (St. Petersburg) and Institute of High-Current Electronics (Tomsk), respectively, have been used in experiments as well as an ion source "TEMP" developed in the Institute of Nuclear Physics of Tomsk Politechnic University. In such a way it appears possible to change the pulse duration from 10^{-7} to 10^{-5} s and depth of penetration of charge particles from tenths to tens microns. Consequently a possibility appeared to investigate the results of modification of titanium $\alpha + \beta$ alloys at heating and cooling rates being changed for some orders of magnitude.

All the most important characteristics of temperature fields being induced during irradiation of titanium alloys were obtained with the numerical solution of one-dimensional non-homogeneous nonliner heat equation taking into account the phase transition of the first order of crystal phase-melt type. It has been established that the utilization of the three above-mentioned sources of surface treatment allows to change the thicknesses of heat-affected zone and melt; melt lifetime; crystallization rate; characteristic times of existence in the material at the elevated temperatures as well as the cooling rate of solid material in range of some orders of magnitude.

1. Introduction

Over the last two decades the intense pulsed electron and ion beams have been widely used for modification of structure and surface properties of $\alpha + \beta$ titanium alloys. By now in this field of investigation a numerous experimental data and data of simulations have been obtained [1–4]. The results in many cases are appealing from viewpoint of their application in industries. Particularly choosing the modes of irradiation in a proper way it turned out possible to enhance the wear and corrosion resistance, fatigue limit, oxidation resistance and heat salt corrosion resistance for parts made from titanium alloys. Unfortunately, sometimes an enhancement of one service performance is accompanied by decreasing of another one.

The problem occurred particularly due to the narrow range of irradiation modes that is restricted by the parameters of utilized electron or ion source. Adjusting the parameters of the source used in experiments the most important characteristics of the heating process such as melt thickness, lifetime of the melt, heat-affected zone (HAZ) thickness, heating and cooling rate it turned out possible to change no more than two- or three-fold. Such range is tuned out to be too short for solution of some problems of material science. Particularly the removing of spent coating away the surface of parts implies an employing of fairly wide range of irradiation modes. These modes should provide both evaporation (powerful irradiation fluxes) of the material on the first stage of treatment and smoothing (weak irradiation fluxes) of the surface on the last stage of treatment. So enlargement of the range of irradiation modes would allow to carry out the complex modification of materials. The work is the first step in this direction. It concerns with comparison of the experimental and simulation results on irradiation of titanium alloys at the different electron and ion beam installations.

2. Parameters of electron and ion beams

Enlargement of range of irradiation modes is attained with employment in experiments of the three unique wide-aperture sources of pulsed electron and ion beams. Two electron beams of "GEZA" and "RITM" developed in the Institute of Electrophysical Apparatus

[1] The work was supported by RFBR Grant No. 07-08-00709.

(St. Petersburg, Russia) and Institute of High-Current Electronics (Tomsk, Russia), respectively, have been used in experiments as well as an ion source “TEMP” developed in the Institute of Nuclear Physics of Tomsk Politechnic University.

Adjustment of parameters for each of the beams used in the work has realized as follows. On one hand the surface of the material has to be melted and the melt thickness should be maximal. On the other hand the noticeable evaporation is not allowed because evaporation leads to an increase in the surface roughness. Based on analysis of experimental and numerical data the following parameters have been chosen as the optimal ones (see Table 1).

It can be seen from the table that pulse duration, particle energy, beam current density and energy density are different from each other by one-two orders of magnitude. Consequently irradiation with these sources will lead to realization of the sufficiently different heating modes.

Table 1. Major parameters of electron and ion beams

Source type	Pulse duration, μs	Particle energy, keV	Current density, A/cm^2	Energy density, J/cm^2	Power density, W/cm^2	Beam radius, cm
GEZA (electrons)	14–35	116	10	18–40	10^6	5
RITM (electrons)	3–4	up to 30	100–150	3–4	10^6	10
TEMP (50% of protons and 50% of carbon ions)	0.08–0.1	up to 200	50–60	0.5–0.6	$6 \cdot 10^6$	3

3. Sumulation

Knowing the particle energy and pulse duration one can calculate the extrapolated depth of particle penetration R_{ex} and the thickness of layer l_q, heated by the heat diffusion, respectively. The latter is determined by the following expression

$$l_q = \sqrt{a\tau}\,, \qquad (1)$$

where a is a heat diffusivity of material.

Let’s consider the parameter $\gamma = R_{ex} / l_q$ characterizing the type of heat source: for $\gamma \ll 1$ a heat source is the surface one, that means the heating is realized mainly by a heat diffusion; for $\gamma \gg 1$ a heat source is the volume one, i.e. the heating is realized as a result of direct energy transfer from the incident particle to the media irradiated. Taking into consideration that a heat diffusivity a for VT6 alloy equals to $5 \cdot 10^{-6}$ m^2/s, one can calculate the parameter γ equals to 2.5, 0.7, and 1.5 for “Geza”, “Ritm” and “Temp” source, respectively. Consequently, in all cases the source is mixed and for calculation of temperature field it is necessary to solve one-dimensional non-homogeneous non-linear heat diffusion equation. The equation taking into account the phase transition solid-melt can be written as follows

$$\rho\left[c(T) + q_m\delta(T - T_m)\right]\frac{\partial T(x,t)}{\partial t} = = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T(x,t)}{\partial x}\right) + L_V(x,t)\,, \qquad (2)$$

where ρ, c, q_m, T_m, and k are the density, the specific heat capacity, the latent heat of melting, the melting point, and the heat conductivity of material, respectively; δ is the Dirac delta-function; L_V is the heat-generation function, determining the amount of energy released in a unit volume per a unit of time.

The latter depends on type of particle incident and their energy and may be written as follows:

$$L_V(x,t) = \frac{j(t)E_0(t)}{R_{ex}(t)e} f(x/r,t)\,, \qquad (3)$$

where $j(t)$ is the current density of charged particles; $E_0(t)$ is the particle energy; e is the particle charge; $f(x, t)$ is a normalized function of in-depth energy losses. Current density of charged particles and their energy were defined experimentally based on oscillograms of beam current and voltage on vacuum diode of the source.

Equation (2), completed with initial and boundary conditions was solved numerically. The results of calculations are described below.

4. Results and discussion

The materials under investigations were titanium alloys VT6, VT8, and VT9. All these materials have close thermophysical parameters and that is why the temperature fields calculated depend weakly on the alloy type and are determined by parameters of the particle beam only. Below the dynamics of heating for the three sources of irradiation will be illustrated for the most common alloy VT6.

In Figs. 1 and 2 the maximal temperature vs. distance from the irradiated surface and surface temperature vs. time can be seen, respectively.

Figure 1 illustrates that the surface layer of thickness ranging from units to hundreds microns depending on type of particle beams is heated as a result of pulsed irradiation. The isotherm $T = 1000$ K being plotted on the Figure intersects each of the temperature curves. Abscise of the intersection point maybe considered as the thickness of HAZ. In this approximation HAZ thickness equals to 1.24, 8.7 and 38.7 μm for the case of irradiation of target with ion (curve *3*) and electron beams generated with "RITM" (curve *2*) and "GEZA" (curve *1*), respectively. In such a way the thickness of HAZ changes by one order of magnitude for different sources of irradiation.

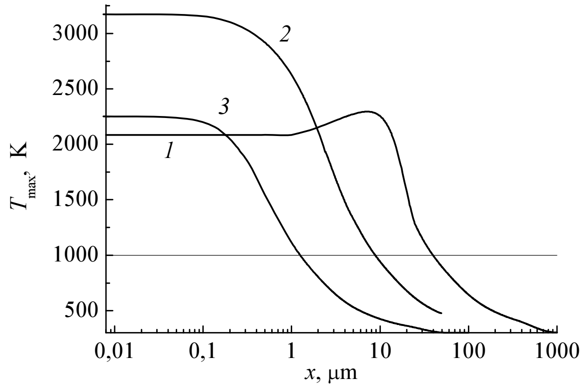


Fig. 1. Maximum temperatures vs. distance from irradiated surface when irradiated of VT6 alloy by electron beams "GEZA" (*1*), "RITM" (*2*), and ion beam "TEMP" (*3*)

Period of time while the material exists at the elevated temperatures maybe estimated from Fig. 2.

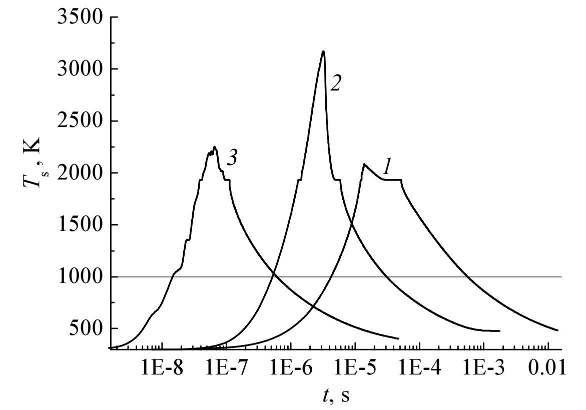


Fig. 2. Surface temperature vs. time for the case of irradiation of VT6 by electron beam "GEZA" (*1*), "RITM" (*2*), and ion beam "TEMP" (*3*)

Temperature at the surface of target holds above 1000 K during 0.6 (curve *3*), 30 (*2*), and 600 μs (*1*) for case of irradiation of the target by ion beam "TEMP" and electron beams "RITM" and "GEZA", respectively. Consequently the range of time intervals while the material exists at the elevated temperatures includes three orders of magnitude. Besides it can be seen from Figure that maximal temperature at the surface in all cases is in the range of 2100–3200 K that is substantially lower than temperatures of noticeable evaporation of titanium alloy.

Both the thickness of heated layer and characteristic times of material existence at elevated temperatures influence on dynamics of the material melt determining its maximal thickness and lifetime. In Fig. 3 the dependence of material melt thickness on time for the three cases of target irradiation by electron and ion beams is seen.

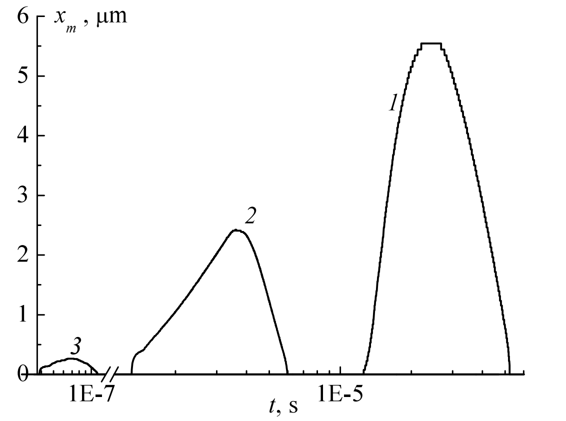


Fig. 3. Melt thickness of VT6 alloy vs. time during irradiation by electron beam "GEZA" (*1*), "RITM" (*2*), and ion beam "TEMP" (*3*)

In Fig. 3, in fact is the state diagram indicating in which liquid or solid phase the given volume of material exists at one or another point of time. The points situated below the curves according to the melt and ones situated above them according to the solid state. It can be seen from the Fig. 3 that maximal depth of the melt of VT6 alloy attaining when irradiated by electron beam "GEZA" (*1*), "RITM" (*2*) and ion beam "TEMP" (*3*) equals to 5.5, 2.4, and 0.27 μm, respectively.

Comparing Figs. 1 and 3 one can make a conclusion that there is a correlation between the thicknesses of HAZ and melt. To the maximal thicknesses of HAZ occurred at irradiation of target by electron beam of "GEZA" type (38.7 μm) corresponds the maximal melt thickness (5.5 μm) reached at the same irradiation. For "RITM" and "TEMP" sources we have the following: HAZ thickness 8.7 and 1.24 μm (melt thickness 2.4 and 0.27 μm), respectively.

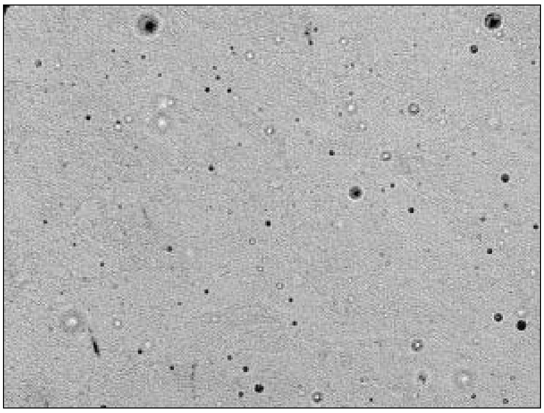
Important, excepting the melt thickness, parameter is the melt lifetime which determines in particular the surface roughness and consequently the service performances of the part. The more time the material surface exists in a liquid state the larger is a probability of getting of smooth and crater free surface. The larger will be the melt and HAZ thickness, the more will be the melt lifetime. It can be seen from Fig. 3 that the melt lifetime at irradiating of VT6 by electron beams "GEZA", "RITM" and ion beam "TEMP" amount to $7.2 \cdot 10^{-8}$, $5.7 \cdot 10^{-6}$, and $4 \cdot 10^{-5}$ s, respectively.

Formation of finishing structure of material after irradiation is the many-stage process depending on many factors particularly on the conditions of its crystallization and cooling in solid state. The larger are crystallization and cooling rates the larger is a probably of formation of metastable phases. Calculated rates of crystallization and cooling for all three types of the sources are listed in Table 2.

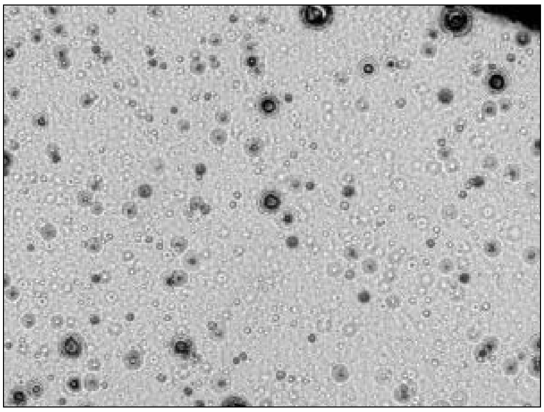
Table 2. Characteristic rates of crystallization and cooling of VT6 alloy

Source type	Crystallization rate, m/s	Cooling rate, K/s
GEZA	0.2	3 · 106
RITM	1.3	107
TEMP	5	3 · 108

It can be seen from Table 2 that the maximal rates of crystallization and cooling are attained at employing of ion source "TEMP" that is explained by a low thickness of HAZ and consequently by a high rate of the heat removing from the irradiated surface. In this case the rates amount to 5 m/s and $3 \cdot 10^8$ K/s, respectively. Minimal rates of crystallization and cooling are realized when irradiated with electron source "GEZA". The latter 25-fold and 100-fold less than that for the ion source "TEMP", respectively.



a



b

Fig. 4. SEM image of VT9 alloy surface irradiated by pulsed electron beam "RITM" (*a*) and by pulsed ion beam "TEMP" (*b*)

The major problem when irradiated the surface with pulsed power is the occurring of cratering.

The cratering can not be allowed because it leads to a sharp decreasing of service performances of parts working at constant and alternative loadings. Cratering takes place owing to inhomogeneity of material and presence in the material the secondary phase inclusions which are its unavoidable satellites. It has been established that there is a correlation between the surface concentration of microcraters and thickness of the melt and its lifetime. The less are the melt thickness and its lifetime the larger is the surface concentration of micocraters. In Fig. 4 are shown the secondary electron microscopy (SEM) images of the surface of VT9 alloy irradiated by pulsed electron beam "RITM" and by pulsed ion beam "TEMP".

It can be seen that after irradiation by "RITM" the number of craters presented is sufficiently less then that for "TEMP". This means that if the melt is sufficiently thick like in the case with "RITM" and exists long time the inclusions are completely dissolved in matrix and surface tension force smoothes the initially rough surface as it can be seen in Fig. 4, *a*. Whereas if the melt thickness and its lifetime are short, for instant, as while irradiating the material by "TEMP" source the crater present at the surface that would be noted in Fig. 4, *b*.

5. Conclusion

Based on simulation of temperature fields in the targets made from VT6, VT8, and VT9 titanium alloys it can be concluded that employment of three unique wide-aperture sources of pulsed electron and ion beams provided a possibility to substantially enlarge the range of irradiation modes. In such a way it appears possible to change the depths of HAZ and melt; melt lifetime; rates of crystallization and cooling as well as characteristic times of existence in material the elevated temperatures by some orders of magnitude. Experiments have been carried out will provide us by invaluable information on behavior of titanium alloys and change their microstructure and properties in the wide range of parameters characterizing the process of high-rate material heating and cooling.

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