Investigation of the effect of ion implantation on the structure of the surface layer of VT20 titanium alloy

V V Ovchinnikov and N V Uchevatkina*

Moscow Polytechnic University, B. Semenovskaya st., 38 Moscow, 107023, Russian Federation

*uchevatkina@yandex.ru

Abstract. The effect of ion implantation of VT20 titanium alloys on their structural and substructural characteristics is studied. A significant change in structural characteristics has been established, which contributes to an increase in the strength properties of alloys with satisfactory ductility and heat resistance. This work was carried out as part of the state task of the Ministry of Science and Higher Education of the Russian Federation «The influence of magnetic fields and ion implantation on the structure, chemical composition and properties of titanium, aluminum alloys and elementary semiconductors».

1. Introduction

Ion implantation is the process of introducing ionized atoms into a target with an energy sufficient to penetrate into its surface regions. The successful use of ion implantation is determined mainly by the ability to predict and control the electrical and mechanical properties of the formed elements under given implantation conditions.

One of the advantages of metal ion implantation is the absence of serious heating (not more than 150 °C) of the implantable target (sample). This allows you to save without changing the structure of the deep layers of the target.

At the same time, the braking of implantable ions in the surface layers of the target will be accompanied by a short-term increase in the surface heating temperature. Since the implantation process is performed in a pulsed mode, during the pause period, a sharp decrease in the surface heating temperature is observed. Moreover, a decrease in temperature occurs with a high cooling rate.

During ion irradiation according to non-stationary regimes of titanium alloys, the following parameters affect the mechanical and structure of alloys: the number of processing cycles, the range of temperature variation in the cycle, heating and cooling rates, and the presence or absence of exposures at extreme temperatures of the range [1, 2].

Changing these parameters during implantation, one can obtain fundamentally different structures in the surface layers of titanium alloys and, accordingly, achieve different properties of these materials.

It can be assumed that obtaining enhanced mechanical properties of VT20 type pseudo-α-titanium alloys is possible as a result of the formation of a finely dispersed globular microstructure similar to the structure of VT6 alloy, which is formed upon hardening by quenching and aging [3-5].

When titanium alloys are heated under non-stationary conditions during the implantation process, the structure and phase composition change under the influence of factors peculiar only to conditions under which the temperature conditions of processing continuously change. These are temperature
gradients, phase transformations, and the associated diffusion fluxes of elements in the alloy, thermal (bulk) and interfacial internal stresses due to the difference in the thermophysical and mechanical characteristics of the phases that make up the alloy.

Phase and structural transformations that develop as a result of cyclical changes in temperature during implantation are accompanied by the appearance, movement, and annihilation of various defects, as well as the redistribution of alloying elements in the alloy. The occurrence of internal stresses and the formation of a special structure and substructure of titanium alloys, which provides them with increased strength, heat resistance and ductility, are also quite likely. It is possible to form a field of internal stresses that affect both the hardening of the alloy and the occurrence of structural phase transformations [6,7].

A cyclic change in the temperature of the target surface activates the process of movement and redistribution of grain boundaries.

2. Materials and methods

When processing titanium alloys of the VT20 type, the temperature range of thermal cycling was selected depending on the purpose of the hardened product, on the physicomechanical properties of the material and its initial structural state.

Temperature exposure was carried out using the IMASH ALA-TOO 20-75 installation, which allows heating samples with a passing current with an industrial frequency in a low-pressure vacuum.

The temperature of the sample was measured using a thermocouple having a junction with a diameter of 0.25 mm. The junction was spot welded to the surface of the sample in the region of maximum heating (Fig. 1). The dimensions of the sample were selected in accordance with the design features of their placement in the installation, as well as to avoid thermal inertia.

![Figure 1. Sample for thermal cycling.](image)

The maximum (upper) heating temperature in the cycle was chosen in accordance with the condition of complete α→β transformation, namely $t_B = \text{Ar}_3 + (30 \ldots 50)\degree\text{C}$, and the lowest temperature in the cycle was taken below the temperature at which the full transition of the high-temperature alloy modification occurs to low temperature.

Heating rates were selected based on the results of preliminary studies and amounted to $V_{\text{nagr}} = 20-22\degree\text{C}/\text{s}; V_{\text{cool}} = 10-12\degree\text{C}/\text{s}$, respectively. The thermal cycling time varied in the range from 1 to 20 minutes, which corresponds to the real range of exposure of the samples during irradiation.

3. Results and discussion

The results of studying the structure of the VT20 alloy subjected to a cyclic change in temperature revealed the occurrence of spheroidization of structural elements of the studied alloy. As a result of thermal cycling, a transition of the initial lamellar structure of the VT20 alloy to a globular structure
was observed for 8 minutes, which includes rounded particles of the α phase and interlayers of the β phase between α particles having an indefinite shape.

After 10 minutes of heating-cooling, the VT20 alloy acquires a structure that includes globular particles of the α phase with sizes of 3.5 ... 4.3 μm and 5.8 ... 6.3% of β-interlayers with sizes of 0.73 ... 0.90 μm between them.

Moreover, the grain sizes of the α phase after 12 minutes of exposure in the VT20 alloy noticeably decrease with a large number of β interlayers (Fig. 2).

The ductility of the alloy under study at high temperature is explained by the increased doping of the β phase, which determines its high stability [8]. This was revealed by the method of MRSA, as a result of which, the content of an increased amount of β-stabilizing elements in the interlayers of the β-phase was revealed, compared with their average concentration in the VT20 alloy.

Figure 2. Microstructures (× 200) of VT20 alloy: а - upon annealing from 880 ° C, for 2 hours; b - as a result of thermal cycling (1100–800 ° C) lasting 8 minutes; c - as a result of thermal cycling (1100-800 ° C), lasting 12 minutes.

It should be noted that as a result of 10 minutes of treatment, the sizes of β-layers are minimized and the continuation of the heat treatment does not decrease further (Fig. 3).

It was also found that the greatest quenching of the titanium alloy under study during thermal cycling occurs at elevated cooling rates, while the heating rate has almost no effect on these parameters. In this case, ω-Ti, α'-Ti, α''-Ti are formed metastable phases, noticeably embrittlemnet alloys. For VT20 alloy, the cooling rate at which metastable phases are formed is 7.3–7.5 ° C / s.

Thermocyclic treatment has a significant effect not only on the structural, but also on the substructural characteristics of the VT20 pseudo-α-titanium alloy [9, 10]. It was established that during the first 2 ... 4 minutes of heating-cooling, polygonization of the primary α-phase plates occurs, new boundaries and dislocations flow to them, stop there and form a grid (Fig. 4, a).

Such a substructure provides enhanced strength properties both at low and at elevated temperatures without the risk of destruction of the implanted VT20 alloy layer [10].
Figure 3. The amount of $\beta$-phase in the VT20 alloy depending on the duration of thermocyclic exposure.

Figure 4. Dislocation structure (x18000) after various durations of thermal cycling: a - 3 minutes; b - 10 minutes.

4. Conclusion
The studies performed allowed us to establish that, during the ion implantation of the VT20 titanium alloy, a cyclic change in the heating temperature of the sample surface occurs, which causes the evolution of the alloy structure from plate to globular with rounded particles of the $\alpha$ phase and the interlayer of the $\beta$ phase between $\alpha$ particles.

As a result of 10 minutes of treatment, the sizes of $\beta$-layers are minimized and the continuation of the heat treatment is not further reduced.

It was established that during the first 2 ... 4 minutes of heating-cooling, polygonization of the primary $\alpha$-phase plates occurs, new boundaries and dislocations flow to them, stop there and form a grid. This structure provides high strength alloy VT20 in a wide range of operating temperatures.

References
[1] Sharkeev Yu P 2000 Long-range effect in ion-implanted metal materials: dislocation structures, properties, stresses, mechanisms Doc. Dis Tomsk, 420 p
[2] Bely A V Kukareko V A Lobodaev O V Taran I I Shikh S K 1998 Ion beam processing of metals, alloys and ceramic materials Minsk: Institute of Physics and Technology 219 p
[3] Lyasotskaya V S Knyazev S I 2000 Polymorphic transformation is the basis of thermocyclic processing of titanium alloys Metallurgy and heat treatment of metals No 4 p 20-23
[4] Lyasotskaya V S Knyazev S I 2009 Thermocyclic treatment of titanium alloys based on
polymorphic transformation. *Metallurgy and heat treatment of metals* No 1 p 9-13

[5] Uchevatkina N V Ovchinnikov V V Zhdanovich O A 2017 The effect of plasma treatment on the surface microrelief of parts made of VT6 titanium alloy *Hardening technologies and coatings* Volume 13 No 1 p 24–29

[6] Panin V E Egorushkin V E 2009 Physical mesomechanics and nonequilibrium thermodynamics as a methodological basis of nanomaterial science *Phys. Mesomechanics* V 12 No 4 P 7–26

[7] Lotkov A I Meisner L L Grishkov V N 2005 Alloys based on titanium nickelide: ion-beam, plasma, and chemical surface modifications *Physics of Metals and Metallurgy* T 99 No 5 p 66-78

[8] Ovchinnikov V Lukyanenko E Yakutina S 2019 Investigation of the Effect of Complex Treatment on the Wear Resistance of Titanium Alloys *Materials Today: Proceedings* T 11 p 359-362

[9] Greshilov A D et al. 2014 Influence of thermocyclic treatment on the properties of cast alloys based on aluminum, tool steel and on diffusion processes during chemical-thermal treatment *Bulletin of VSGUTU* No 5 P 59

[10] Lyakhov AV Gadalov V N Makarova I A Elnikov E A Erokhin R Y Gvozdev A E Kutepov S N Pantyukhin O V 2018 Investigation of the influence of thermocyclic processing on sintered PSEVDO-a-TITANIUM alloys *Izvestia T. Technical science* No4 p 219-227