

High-intensity implantation of aluminium ions into VT1-0 titanium alloy

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Abstract. Structural and phase state of VT1-0 titanium alloy surface layers with different initial grain sizes before and after ion implantation with aluminum ions at the high-dose implantation mode was studied. Implantation of aluminum ions into VT1-0 titanium alloy made it possible to form surface layers with improved performance properties.

1. Introduction

Ion implantation is an effective method of increasing the characteristics of structural and instrumental materials by changing the elemental composition and structural and phase state of surface layers of metals treated with an ion beam. A very promising direction of ion implantation is the formation of intermetallic systems characterized by abnormal high-temperature properties in the surface layers. Intermetallic compounds retain the structure and strength at high temperatures and have good anti-corrosion and anti-friction properties, so they are much superior to conventional materials [1-4].

This article contains studies of VT1-0 titanium alloy samples implanted with aluminum ions to create modified layers characterized by high heat resistance and wear resistance, which is very important for a number of parts of gas turbine plants.

The objective of the work is to study the microstructure and phase composition of VT1-0 titanium alloy surface layers depending on the conditions of implantation of aluminum ions.

2. Materials and methods

The implantation of aluminum ions into VT1-0 titanium samples prepared according to the traditional method is performed in the modes given in Table 1.

Table 1. Modes of aluminum ion implantation into VT1-0 titanium alloy

System	Accelerating voltage, kV	Sample surface heating temperature, °C	Distance from ion source to samples, m	Duration of implantation, min	Irradiation dose, 10^{17} ion/cm ²
Ti-Al	30	870	0.52	15	2.4
				38	7.1
				64	12.6



Three series of experiments were performed differing in the time of treatment and dose of irradiation of the samples (Table 1). The elemental composition of the implanted samples was studied using the Auger electron spectroscopy (AES).

The structural and phase state of implanted samples was studied by transmission electron microscopy (TEM). The sizes of grains formed during the implantation of phases are determined by the “secant” method [5] on the dark-field TEM images.

The microhardness measurement was performed using measuring device “Nano Hardness Tester NHT-S-AX-000X” of the Swiss company “CSEM”. The technique uses the Vickers nanoindentators. The load on the indenter varied from 15 to 280 mN.

3. Results and Discussion

When aluminum ions were implanted into VT1-0 titanium alloy, it was possible to obtain ion-doped surface layers with a thickness of 280-1380 nm depending on the irradiation dose (Figure 1).

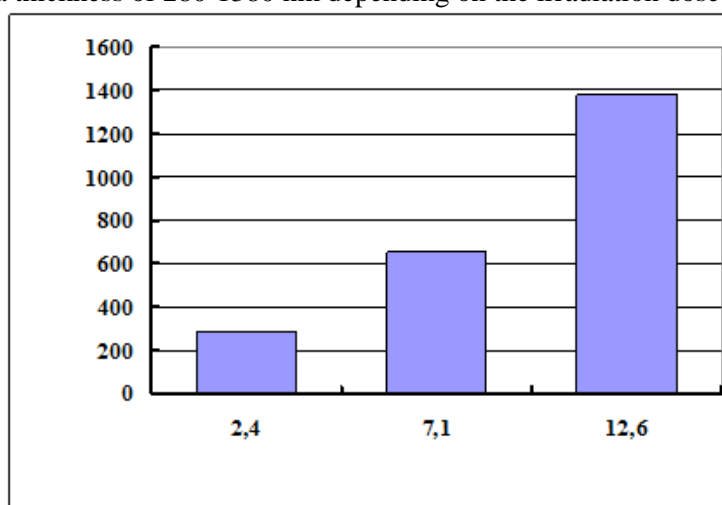


Figure 1. Effect of the dose of irradiation with aluminum ions on the thickness of ion-doped layers of VT1-0 titanium alloy

The maximum concentration of aluminum in the surface layer of a VT1-0 titanium alloy sample at a dose of implantation of 2.2×10^{17} ion/cm² is 36 at. % and fall to a depth of 95 nm from the irradiated surface. With distance from the implanted surface layer deep into the target, the aluminum concentration decreases sharply and does not exceed 4 at. % at a distance of 215 nm from the irradiated surface.

With increase in the irradiation dose, the aluminum concentration in the surface layers increases to 56-58 at. % and the concentration maximum shifts to a region of greater depths. So, the maximum is at a depth of 270 nm in the case of implantation with an irradiation dose of 7.1×10^{17} ion/cm² and at 420 nm from the irradiated surface at an irradiation dose of 12.6×10^{17} ion/cm².

In addition to aluminum ions, in the surface layers there are impurities of oxygen and carbon (apparently from the residual atmosphere of the vacuum system). The presence of oxygen and carbon contributes to the formation of oxides of titanium and aluminum, as well as titanium carbide [6].

Study of the structural and phase state of ion-doped titanium layers under all conditions of implantation by transmission electron microscopy showed the existence of phases of α_2 -phase (intermetallic Ti₃Al) and γ -phase (intermetallic TiAl); solid aluminum solution in hexagonal titanium (α -phase). Formation of these phases in the titanium surface layers is consistent with the phase diagram of the Ti-Al system [7-8].

The microdiffraction pattern of a VT1-0 titanium alloy sample implanted at an irradiation dose of 2.4×10^{17} ion/cm² is a set of diffuse rings; it is associated with the formation of finely dispersed intermetallic phases of Ti₃Al and TiAl with uniform distribution over the depth of the doped layer.

The average size of grains of the phases formed was 25 nm. With an increase in the irradiation dose, an increase in the average grain size of grains of the phases formed and their unification into conglomerates occurs; it leads to the appearance of a multitude of point reflexes on the Debye rings of microdiffraction patterns [9].

At the maximum dose of irradiation with aluminum ions, the grains of the intermetallic phases formed have an average size of about 43 nm, and the average size of the conglomerates reaches 180 nm. Comparison of the light-field and dark-field images of implanted surface layers of VT1-0 titanium alloy showed that the Ti_3Al phase crystallites are formed next to TiAl possibly due to the phase transition of α_2 to γ -phase. Locations of the phases formed were determined based on the data obtained by AES methods.

There is a gradual transformation of the structure of VT1-0 titanium alloy implanted layer as the dose of irradiation with aluminum ions increases.

Directly on the target surface, there is an oxide-carbide film, which arises from the interaction of the target metal heated during implantation with residual vapors of the implantation chamber. The thickness of this film increases with increasing dose of implantation when using oil-vapor pumps to create vacuum, and remains more or less constant when the chamber is pumped by turbomolecular pumps.

Directly underneath this film there is a sub-layer, which contains two intermetallide phases (α_2 - Ti_3Al ; γ - TiAl) and a solid aluminum solution in titanium; α_2 -phase (Ti_3Al) is formed at large distances from the surface in contrast to the γ -phase of TiAl (the region located below this sublayer). It can also be noted that a solid solution of aluminum in titanium (α -phase) is formed throughout the entire depth of the implanted layer.

The study of mechanical properties showed that the microhardness at depths of up to 1.5 μm exceeds the microhardness at the corresponding depths for initial titanium in all implanted samples of VT1-0 titanium alloy. For a sample with a processing time of 64 min, an increase in microhardness of 1.1 ... 1.9 times was observed in the near-surface region with a thickness of $\sim 1.5 \mu\text{m}$.

It was found that with a decrease in the grain size, i. e. with an increase in the density of boundaries in the alloy, the microhardness of the initial VT1-0 alloys increases (Figure 2).

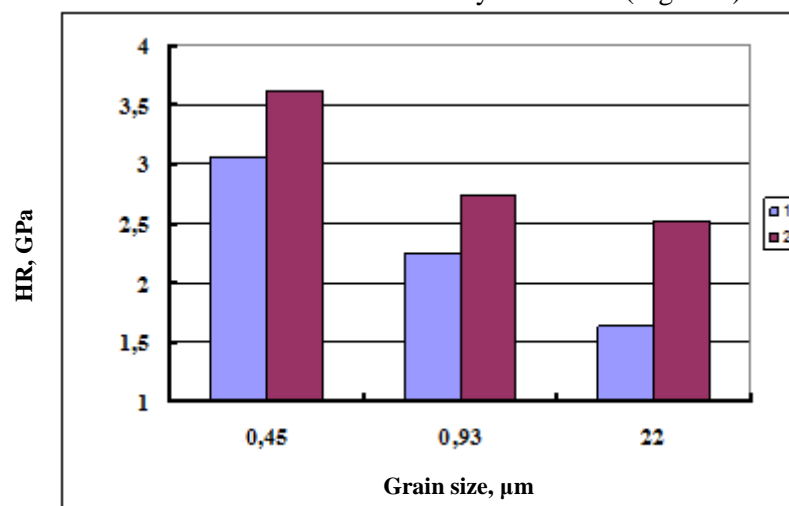


Figure 2. Microhardness of titanium samples before (1) and after (2) ion implantation

It is clearly seen that in VT1-0 alloy with a grain size of 0.45 μm , in which the density of the boundaries is the greatest, the microhardness is of the greatest importance. In the alloy with a grain size of 22 μm having the largest grain size, i. e. the smallest density of boundaries, microhardness has the smallest value. The results obtained are in good agreement with the results on the hardening of these alloys. At the level of grain sizes (less than 1 μm), the contribution to microhardness, a high

concentration of grain boundaries, begins to make a great figure. In this case, the defective structure of grain boundaries becomes the most important factor.

After ion implantation, a significant increase in microhardness is observed, and the largest increase occurs in the alloy with a grain size of 22 μm , and this also agrees with the results described above. The increase in microhardness of implanted alloys is associated with hardening due to the formation of nanocrystalline aluminide phases in the volume of matrix grains. Additional stabilization of the structure of materials with grain parameters in the micro-region occurs by fixing grain boundaries and their joints with intermetallic phases, it gives a significant hardening [10].

Table 2 shows the potentials and currents of corrosion calculated from the curves obtained in the potentiodynamic mode (cyclic voltammetry mode). Corrosion currents for implanted titanium are much smaller for titanium samples in submicrocrystalline and fine-grained states in all media. For VT1-0 titanium alloy with a grain size of 11.4 μm , this regularity is preserved in acidic and neutral media, for titanium alloy with a grain size of 22 μm – only in a neutral media. Thus, when comparing implanted and non-implanted titanium, it is seen that the size of the matrix influences the electrochemical behavior of metals, while in general the implanted samples have a higher corrosion resistance.

Implantation of the titanium surface with ions of a more active metal – aluminum – with respect to the matrix provided that the formation of intermetallic compounds and passivation processes do not usually lead to a decrease in corrosion resistance. In this case, the mechanism of electrochemical corrosion is more complicated because, firstly, intermetallic compounds are formed in the near-surface layers of titanium, and secondly, both titanium and aluminum are prone to passivation both in air and in many electrolytes [11].

Table 2. Potentials and corrosion currents for titanium in various media

Grain size, μm	0.1 M HCl		0.1 NaNO ₃		0.1 M NaOH	
	E_{cor} , B	I_{cor} , mA/cm ²	E_{cor} , B	I_{cor} , mA/cm ²	E_{cor} , B	I_{cor} , mA/cm ²
Non-implanted VT1-0 titanium alloy						
0.45	0.0068	0.07	−0.09	2.74	−0.170	2.88
0.93	−0.155	0.75	−0.27	0.41	−0.460	0.71
11.4	−0.276	0.02	−0.24	0.45	−0.472	0.26
22	–	–	−0.14	0.22	−0.755	0.54
Implanted VT1-0 titanium alloy						
0.45	−0.420	0.022	−0.715	0.01	−0.644	0.18
0.93	−0.242	0.07	−0.773	0.11	−0.841	0.18
11.4	−0.271	0.01	−0.686	0.10	−0.491	0.41
22	−0.145	0.11	−0.811	0.07	−0.419	0.69

Thus, it was shown that a decrease in the corrosion resistance when aluminum is introduced into the titanium matrix is observed only for titanium with a grain size of 11.4 μm or more. At a smaller grain size, aluminum does not reduce the corrosion resistance of titanium and also in most cases contributes to a significant reduction in corrosion currents.

4. Conclusion

Thus, the high-intensity ion-beam treatment mode for doping of the VT1-0 titanium alloy targets with aluminum makes it possible to obtain layers, thickness of which exceeds the value of the projected range of ions by orders of magnitude. Formation of ion-doped layers of up to 1.5 μm in thickness was observed when implanting aluminum ions into titanium.

Dependence of growth of the thickness of ion-doped titanium and nickel layers on the conditions of implantation was established. The increase in thickness of ion-doped titanium layers occurs with the increase of the material treatment time.

Implantation of metal ions is an effective method for the formation of metal layers containing nanocrystalline intermetallics in surface layers.

Implantation of aluminum ions in VT1-0 alloy leads to a significant increase in microhardness in the surface layers of titanium.

Increase in the target temperature due to the high ion flux density, as well as the duration of the ion treatment, allows the formation of modified layers with a thickness of up to a few micrometers. Such surface layers containing a high density of nanoscale intermetallic phases have significantly better stress-related properties than initial materials of targets.

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