

Influence of the Grain Size on the Dispersion Strengthening of VT1-0 Alloy Implanted with Aluminum Ions

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Keywords: microstructure, grain, phase, titanic alloy, hardening.

Abstract. The method of translucent diffraction electronic microscopy conducted researches of a microstructure and phase structure of a titanic alloy of VT1-0 implanted by ions of aluminum. There are two types of grains; 1) large grains (LG) with an average size of 1.4 microns and 2) the small grains (FG) with an average size of 0.5 μm . It is established that as a result of radiation the ion-alloyed layer, on the basis of α -Ti grains is formed. The sizes, form and places of localization of secondary phases (Ti_3Al , Al_3Ti and TiO_2) depend on the size of grain of a titanic matrix. The size of dispersive hardening of σ_{or} for different type of grains on depth of the ion-alloyed layer is calculated. It is shown that in MZ the size σ_{or} is provided only with TiO_2 particles, in LG – generally TiO_2 particles.

Introduction

It has been established by now that the strength of any metal material is determined by numerous factors [1], one of which is the presence of carbide and oxide particles and other secondary phases in the material. It is also known that the number of present particles, their size, distribution pattern and interparticle distance, as well as the irregularity degree of the matrix lattice and precipitation have an effect on the material dispersion strengthening [2]. Dispersion strengthening mechanisms have been developed for non-coherent particles, when dislocations pass precipitations, and coherent particles, when dislocations may intersect particles. Moreover, dispersion strengthening mechanisms are divided into main (particles are inside the grains) and indirect (particles are at grain boundaries and intersections). Main mechanisms lead to the increased alloy yield limit, while indirect ones have an effect on strength and hardness. In all abovementioned cases a simplified Orowan equation [3] can be used for the calculations of dispersion strengthening: $\Delta\sigma_{\text{or}} = 2\lambda Gb/r$, where $\lambda = 0.5$ – coefficient accounting for all abovementioned factors, $G = 41,000$ MPa – elasticity; $b = 0.346$ nm – Burgers vector; r – interparticle distance.

It was shown [4] that aluminum ion implantation to titanium leads to the formation of a whole set of phases. It was established that the set of phases depends on the grain size, and, hence, dispersion strengthening will vary in differently sized grains. Therefore, it is interesting to examine the behavior of the material with two types of grains available simultaneously.

Experimental Part

The subject of research was VT1-0 grade titanium samples prepared by the method of *abc*-compaction combined with rolling and exposed to additional annealing at 773 K. The material

implantation with aluminum ions was performed at the ion source MEVVA-V.RU at a temperature of 623 K, accelerating voltage 50 kV, ion beam current density 6.5 mA/cm², and a distance of 60 cm from the ion-optical system. The exposure dose ($1 \cdot 10^{18}$ ion/cm²) was achieved by the time of exposure equal to 5.25 h. The structure and phase composition were studied at transmission electron microscope EM-125K at an accelerating voltage of 120 kV at the initial state (prior to implantation) and in two areas of the modified layer: area 1 at a depth of 0-150 nm (the subsurface part) and area 2 at a depth of ~300 nm from the irradiated surface (the modified layer central part).

Results

VT1-0 alloy was prepared in the conditions leading to the formation of two types of grains which are also retained after the implantation (Fig. 1). Type 1 grains are sized within 0.1-0.5 μm (let us denote them as small grains, SG). The average size of small grains amounts to 0.40 μm . Type 2 grains are sized within 0.5-4.0 μm (let us denote them as large grains, LG). The average size of large grains amounts to 1.40 μm . The portion of SG is not great and amounts to 10%. SG are mostly located at LG ternary boundary intersections.

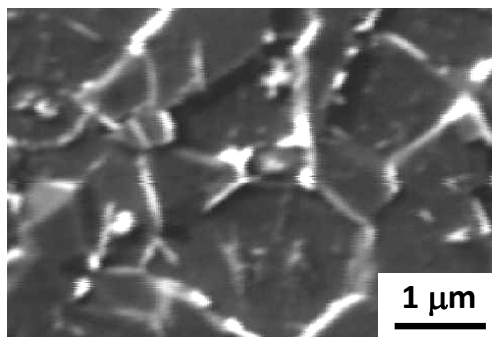


Fig.1. SEM-image of the initial titanium sample

Aluminum ion implantation leads to the modification of elementary composition in titanium surface layers. Alloying admixture (aluminum) is distributed irregularly both throughout the depth of implanted layers and relative to titanium small and large grains. At first aluminum forms a solid solution, with its concentration being in ratio with the size of a matrix Ti grain. Small grains are depleted in aluminum relative to large ones. As a result of irregular distribution of the alloying admixture throughout the material, the phase composition in SG and LG must be different. Indeed, as it was shown earlier [4], implantation led to the formation of a set of phases which is determined by both an investigated area at the sample and the grain size. Namely, there are secondary phases Ti_3Al and TiO_2 in the subsurface part of the modified layer (area 1) together with α -Ti grains. Precipitations of Ti_3Al -phase (an ordered phase with superstructure D0_{19}) have a prolonged shape and mostly located along the α -Ti LG boundaries with the volume ratio being not more than 1% vol. (refer to the Table).

Precipitations of Ti_3Al -phase were found in α -Ti SG neither inside nor along their boundaries. The second phase present in area 1 was the phase of TiO_2 titanium oxide (brookite) having a trimetric crystalline lattice. It should be noted that TiO_2 is also present in the initial titanium prior to ion implantation. Two types of titanium oxide particles were found. The first type is round particles located at dislocations both inside α -Ti LG and SG (volume ratio 1.5% vol.). The TiO_2 particles of the second type have a platelet shape. They are located only inside α -Ti LG with the volume ratio up to 1.5% vol. The sizes of TiO_2 particles are shown in the Table.

There are secondary phases Ti_3Al and TiO_2 in the central part of the implanted layer (area 2), similarly to area 1. However, the average size, volume ratio, and shape of the phases are different (refer to the Table). Nano-grains of Ti_3Al phase are of isotropic shape, sized ~60 nm, but their volume ratio is significantly higher (3.5% vol.). They are mostly located at the ternary boundary intersections of α Ti large grains. As for the particles of TiO_2 oxide, their shape and localization are

similar to that in area 1, but the average size and volume ratios are higher in LG, while in SG they remain constant (refer to the Table).

Table. Phase composition and quantitative characteristics of the phases present in large and small grains of different areas of an α -Ti implanted Al-ions

No	Grain α -Ti	Ti ₃ Al			TiAl ₃			TiO ₂					
		d, [nm]	r, [nm]	δ , [%]	d, [nm]	r, [nm]	δ , [%]	rounded			lamellar		
								d, [nm]	r, [nm]	δ , [%]	d, [nm]	r, [nm]	δ , [%]
I	LG	60×200	608	1.0	-	-	-	20	40	1.5	30×110	175	1.5
	SG	-	-	-	-	-	-	10	20	1.0	-	-	-
II	LG	60	138	3.5	20×60	96	1.2	30	60	2.3	40×250	201	4.2
	SG	-	-	-	-	-	-	15	36	1.0	-	-	-

Note: *d* – average particle size; *r* – distance between the particles; δ – particle volume fraction of the corresponding phase (dash indicates the absence of the corresponding phase)

In area 2 of the implanted layer the phase of TiAl₃ was found, which is an ordered phase with superstructure D0₂₂ having a body-centered tetragonal lattice. Phase TiAl₃ is formed as platelet precipitations along the boundaries of α -Ti LG (its quantitative parameters are shown in the Table). Thereby, implantation of Al into Ti with LG leads to the formation of secondary phases (Ti₃Al TiAl₃). The total number of Ti₃Al and TiAl₃ phases in the I-region is 3% of the volume of material and in the II region – 10%. Formation of Ti₃Al phase is observed throughout the volume of the ion-alloyed layer. Formation TiAl₃ phase occurs only in the middle region of the implanted layer at the grain boundaries (in the region II). These phases were not formed in SG. The oxides TiO₂ formed in all grains and throughout the volume of the ion-alloyed layer.

As follows from the aforementioned, large and small grains differ not only in terms of phase composition, but also in terms of their quantity. This difference is retained throughout the volume of ion-doped layer. Figure 2 shows the behavior of volume ratios in precipitated secondary phases as the grain size grows. It is obvious that, first, the greater the grain size, the more the ratio of precipitated phases; second, in area 2 of ion-doped titanium layer the volume ratio of precipitated phases is always higher; and, third, in each area of titanium ion-doped layer and each type of grains TiO₂ particles prevail.

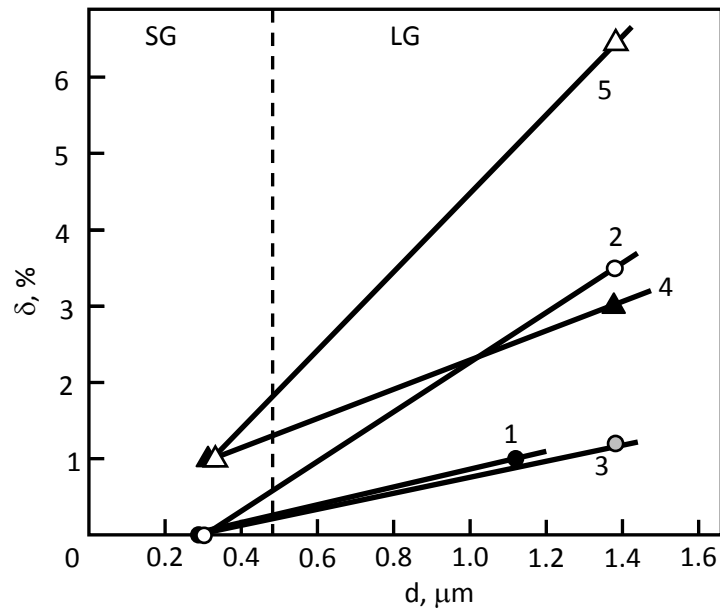


Fig.2. The volume fraction of secondary phase Ti_3Al (1,2), $TiAl_3$ (3) and TiO_2 (4,5) in depending on the grain size of α -Ti: 1,4 - I region; 2,3,5 - II region

All this leads to the fact that the value of dispersion strengthening will be different in LG and SG throughout the modified layer. Based upon the obtained quantitative parameters of the structure, the value of dispersion strengthening σ_{or} was calculated by the abovementioned formula separately for LG and SG. The calculation results are given in Fig. 3. It should be noted that, as reported earlier, at the initial state, regardless of the grain size, VT1-0 alloy is completely single-phase, α -Ti. Hence, there is no contribution into the material strengthening stipulated by the presence of $\Delta\sigma_{or}$ secondary phases. It is seen from the figure that ion implantation both in LG and SG leads to a significant strengthening throughout the implanted layer. However, the influence of the grain size on the value of σ in areas 1 and 2 is different. In particular, close to the surface of ion-doped layer (in area 1) the value of σ decreases as the grain size grows, and in area 2 it goes up.

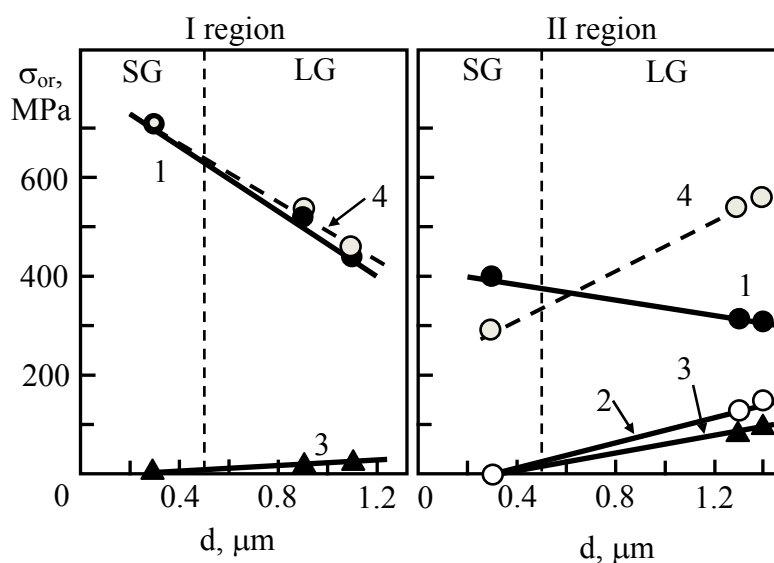


Fig.3. Precipitation hardening σ_{or} depending on grain size α -Ti depth of ion-alloyed titanium layer (in the region I and II) by particles: 1 – TiO_2 ; 2 – $TiAl_3$ и 3 – Ti_3Al ; 4 – the total value of σ_{or} . Vertical dashed line divides areas of small and large grains

Conclusion

As a result of the conducted research it was established that, first, throughout the ion-doped layer the strengthening σ_{or} in SG is ensured exclusively by TiO_2 particles, and in LG these particles make the main contribution. Second, as the distance from the surface grows deeper inside the ion-doped layer, regardless of the grain size, the contribution into σ_{op} made by is reduced, whereas that of Ti_3Al and $TiAl_3$ increases. Third, the overall value σ_{or} in SG decreases as the distance from the ion-doped layer surface grows, while in LG it increases.

Acknowledgments

The work was performed within the framework of governmental contract No 3.295.2014/K of Education and Science of the Russian Federation.

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