The Influence of the Ion Current Density on the Change of the Mechanical Properties and Composition of the Titanium Alloy Surface

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Abstract – The influence of the Si and Ar ion irradiation ($E = 40$ keV, $D = 10^{17}$ ion/cm^2) at the density of ion current in the range of 10–50 μA/cm^{2}on the mechanical properties and composition of the surface layers of the titanium alloy OT4 has been investigated. A non-monotonic change of microhardness and fatigue strength depending on the type and density of ion current has been shown. In the surface layers, the redistribution of the alloy components has been observed at different densities of ion current.

1. Introduction

During operation many components, machine units and entire constructions undergo alternate loads which are much less than yield strength of the materials; under the action of the alternate load the crack development starts from the surface leading ultimately to a failure of an item. Since at bending the amplitude of stresses in the surface layer is minimal, the change of the composition and microstructure of the surface and near-surface layers of the material caused by ion implantation can influence the dynamics of the crack formation and development; consequently, ion irradiation can influence the material fatigue strength [1]. However, the influence of the irradiation parameters (dose, current density and energy of ions) has not fully been understood, and the criterion for choosing an implanted ion type leading to an increase of the metal and alloy fatigue strength has not been determined yet.

Earlier we have investigated the influence of the Si^+ and Ar^+ irradiation dose on the change of the titanium alloy mechanical properties [2]. Silicon and argon were chosen as implants due to their relatively large atomic mass (for the creation of a large cascade area at the interaction with the matrix) and the best mechanical properties of the compound Ti-Si [3].

The purpose of this work is the comparative study of the influence of the Si^+ and Ar^+ ion current density on the mechanical properties and composition of the titanium alloy surface.

2. Experimental

The samples were the plates with 60 mm in length and with a section of 8 × 1.6 mm^2 cut out from a supplied sheet by means of spark cutting. The initial state composition of the samples was Ti – 3.4 mass % Al – 1.0 mass % Mn with insignificant impurities of iron and silicon. The samples were mechanically polished with the use of polishing paste and cleansed in organic solvents [4]. Then some samples were irradiated with Si^+ ions and the rest – with Ar^+ ions. Both sides of the samples were irradiated with the ion energy of 40 keV to the integral dose of 10^{17} ion/cm^2 in the ion current density range of 10–50 μA/cm^2 in the vacuum about 10^{-3} Pa using the ion-beam device ILU (Russian Scientific Center "Kurchatovsky Institute".

The fatigue strength testing was conducted in accordance with the scheme of console bending to failure. Maximal stress over the sample section was 240–370 MPa at frequency of 22.5 Hz.

The distribution of the elements in depth was investigated by means of the secondary-ion mass spectroscopy method (SIMS) using the mass-spectrometer MC-7201M. The atomization of the surface was performed by means of the argon ions with the energy of 4.5 keV at the current density of 50 μA/cm^2. The computed rate of etching was 3 nm/min. The microhardness of the surface layers was determined by forcing a diamond indenter at loading of 20 g into the material and measuring hardness indentation using the device PMT-3.

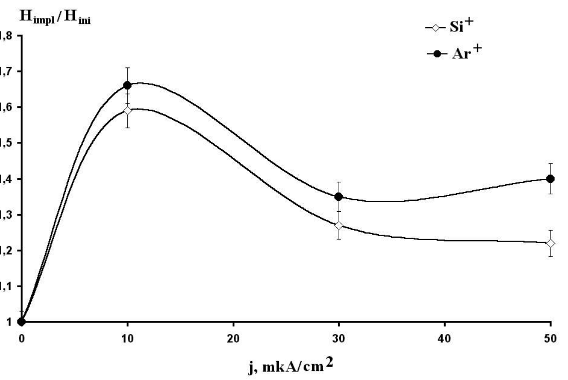

Fig. 1. The dependence of the titanium alloy micro-hardness on the silicon and argon ion current density

3. Results and Discussion

The phase composition of the samples in the initial state was studied by the *x*-ray structure analysis and it showed that the samples consisted of α-phase. The size of grains was 10–16 μm throughout the bulk of the samples.

In Fig. 1, the ion current density dependences of micro-hardness for the samples irradiated with silicon and argon ions are displayed. As is seen from the figure, a maximal ~1.6 times increase in micro-hardness is observed at the minimal density of ion current 10 μA/cm^2 both for silicon ions and for argon 50 μA/cm^2, the ratio $H_{implant}/H_{ini}$ decreases down to ~ 1.2–1.4 at the irradiation with silicon ions and argon ions, respectively. It is believed that the micro-hardness increase during irradiation occurs due to the intensive formation of radiation-induced defects, especially during the irradiation with Ar^+ heavy ions, and the formation of the energy barrier, which anchors dislocations [5]. Besides, at the Si^+ ion irradiation, the strengthening is possible because of the formation of silicon and titanium compounds. It is quite possible that with the ion current density the rate of surface atomization grows which leads to a reduction of the concentration of the implanted impurity in the surface layers, and thus, to a decrease in micro-hardness of the implanted samples [6].

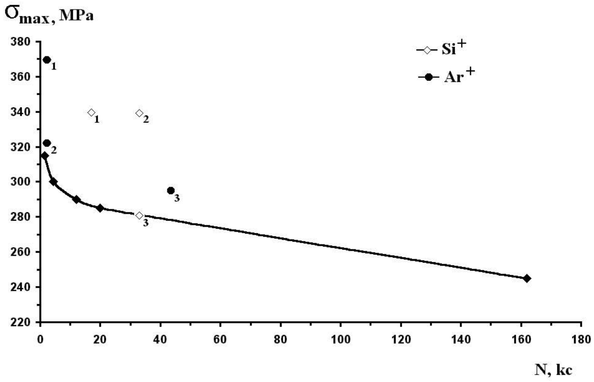

Fig. 2. The results of the fatigue testing for the unirradiated samples and the samples irradiated with argon and silicon ions (1 – 10, 2 – 30, 3 – 50 μA/cm^2)

In Fig. 2 the fatigue testing results for irradiated and unirradiated samples are shown. The irradiated samples stand larger number of cycles before failure than the unirradiated ones. The sample irradiated with silicon ions at j = 30 μA/cm^2 stood twice as many cycles before failure as the sample irradiated at j = 10 μA/cm^2 at the same stress (340 MPa); with the increase of the ion current density to j = 50 μA/cm^2, the fatigue strength reduces; however, it is still larger than that for the unirradiated samples. At the argon ion irradiation, a significant increase in the fatigue strength is attained at j = 10 and 50 μA/cm^2; when the argon ion irradiation is conducted at j = 30 μA/cm^2, the fatigue strength approximately equals to that in the initial state.

On mechanical loading, the redistribution of elements in the surface layers occurs [7]; the aluminum and silicon atoms diffuse to the surface through defects, which are formed during ion irradiation. Since the coefficient of surface tension of silicon (729 mJ/m^2) and aluminum (860 mJ/m^2) is less than that of manganese (1090 mJ/m^2) and titanium (1548 mJ/m^2) [8], the silicon and aluminum segregation leads to a decrease in the free surface energy.

4. Conclusions

1. The change of the fatigue strength depending on the Si^+ and Ar^+ ion current density has been revealed for the titanium alloy samples. A maximal increase in the fatigue strength takes place during silicon ion irradiation at the density of 30 μA/cm^2. The increase in the fatigue strength of the alloy under study is due to the change in the composition and structure of the surface layers and the surface smoothing and microcrack healing at ion implantation.

2. Ion implantation leads to an increase in micro-hardness by 20–60% depending on the current density and a type of ions. Micro-hardness becomes maximum during silicon ion irradiation as well as argon ion irradiation at the current density of 10 μA/cm^2.

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