

Ultrasonic Surface Treatment of Titanium Alloys. The Submicrocrystalline State

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Abstract. The paper presents the results of the research on improvement of physical-and-mechanical properties of titanium alloys VT1-0 and VT6 by modification of surfaces using ultrasonic treatment, and a comprehensive study of the microstructure and mechanical properties of modified surface layers. It has been established that exposure to ultrasonic treatment leads to formation in the surface layer of a structure with an average size of elements 50 – 100 nm, depending on the brand of titanium alloy.

1. Introduction

Currently, in the literature it is shown that refinement of a grain structure up to submicro and nanocrystalline states in metals and alloys leads to significant changes in physical-and-mechanical properties (increase in the yield point and the stress limit, improvement of tribological characteristics, and other) [1]. For example, in papers [2,3] a monotonous increase in the microhardness with an increase in the dispersion of the grain structure has been shown on the example of titanium alloys. In this connection, on the surface of metals it is possible to form submicro- and nanocrystalline states. Such surfaces possess high performance properties. One of the most promising methods in this area is the ultrasonic surface treatment [4]. Titanium-based alloys are very promising in this area. The aim of the work is to carry out structural studies of the effect of ultrasonic treatment on physical-and-mechanical properties and on the microstructure of titanium alloys VT1-0 and VT6.

2. Materials and Research Methods

Titanium-based alloys VT 1-0 (α - phase) and VT6 ($\alpha + \beta$) were used in the study. Samples of alloys VT 1-0 and VT6 were incubated for 1 hour at temperatures of 680 °C and 750 °C, respectively, followed by air cooling.

Ultrasonic surface treatment of samples was carried out using an ultrasonic processing kit UZTK-02. The kit consists of an ultrasonic generator UZG-02/22 and a tool which includes: a magnetostrictive transducer PMS-063 and an indenter. A special ultrasonic impactor tool was installed into a toolholder of the machine (Fig. 1). Technical characteristics of the ultrasonic equipment: capacity – 0.25 kW; ultrasonic transducer - magnetostrictive; operating frequency – 22 kHz; inverter cooling - air; cooling air flow rate – 30 m at a pressure of not less than 0.3 MPa.



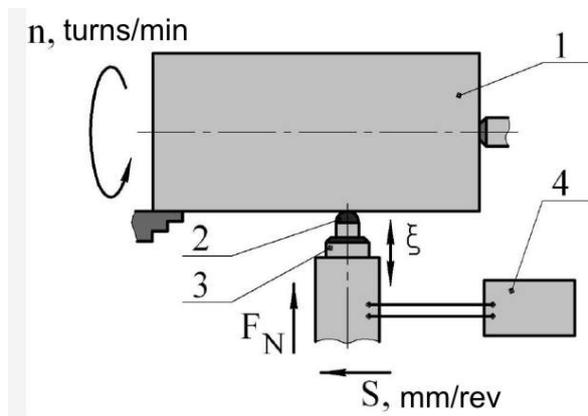


Figure 1. The scheme of ultrasonic surface treatment: 1 – treated workpiece, 2 – ball made of hard alloy, 3 – magnetostrictive transducer, 4 – ultrasonic generator

The metallographic study of the surface structure of titanium samples was carried out using an electronic inverted universal metallographic microscope Axiovert 200 MAT / M MAT (Carl Zeiss). Electron microscopic studies of the structure of titanium alloys were carried out using an electron microscope JEM-200FX.

Prior to ultrasonic exposure the titanium samples were mechanically treated on a lathe under the modes shown in the table 1. For formation of an inclination angle of lateral surfaces of ridges the parameters of lathe turning were varied: longitudinal feed of the slide S which sets the distance between separate ridges of the forming surface microrelief and the angle at the tip of the cutter.

Alloy brand	N of the sample	Cutting speed V , m/min	Longitudinal feed of the cutter S , mm/rev	Angle at the tip of the cutter ε , degrees
VT1-0	1	55	0,1	45
	2	55	0,1	60
	3	55	0,1	90
	4	55	0,2	45
	5	55	0,2	60
	6	55	0,2	90
VT6	1	55	0,1	45
	2	55	0,1	60
	3	55	0,1	90
	4	55	0,2	45
	5	55	0,2	60
	6	55	0,2	90

Six samples of each brand of titanium alloys with different surface microgeometry were prepared for the study of the effect of preliminary surface roughness of titanium alloys on the surface hardening process during ultrasonic treatment. Samples had a cylindrical shape with a diameter of 40 mm and a height of 20 mm. The outer cylindrical portion of the sample were subjected to treatment. Surface treatment of titanium alloys was carried out using different cutters depending on the brand of titanium (VT1-0 samples were treated using cutters R6M5; samples VT6 using the alloy VK6).

The microgeometry of the surface formed as a result of mechanical treatment depends on the geometry of the tool and the feed, as well as on other factors significantly altering the theoretical profile. The latter include: elastic and plastic deformations, friction on the rear surface of the tool, outgrowth, vibrations, and changes in the contour of the blade during its wear. However, in this study the factors influencing the process of microgeometry formation generated by the cutting process and the factors that depend on the equipment and the quality of tools were excluded from consideration. Only factors determining the geometric formation of the residual ridge were taken into account.

In this regard, the variable parameters during lathe treatment were the longitudinal feed of the slide S , which sets the distance between separate ridges of the formed surface microrelief, and the angle δ - the angle at the tip of the cutter which forms an inclination of lateral surfaces of ridges. It should be noted that treatment of titanium alloy VT1-0 was carried out using a cutter with a cutting part made of high-speed steel R6M5. However, during treatment of titanium alloy VT6 the tip of the abovementioned cutter broke down immediately, not allowing to perform the intended treatment. In this connection, for treatment of the alloy VT6 the cutter was replaced with a cutter with a cutting part made of hard alloy of the brand VK6.

3. Results and Discussion

The indenter under the static and dynamic force generated by an oscillating system plastically deforms the surface layer of the workpiece preliminary treated by cutting. Surface treatment of the workpiece was carried out using a hard-alloy indenter oscillating with an ultrasonic frequency. In the area of the local contact of the indenter with the treated surface a plastic deformation zone occurs which shifts together with the indenter. All samples were treated under the same mode in order to eliminate the influence of modes of the ultrasonic treatment on the structure of the forming hardening layer.

The process of development of plastic deformation during the collision of a single indenter with an elastic-plastic material with known physical-and-mechanical properties and roughness consists of three stages. At the first stage the load is concentrated on ridges of microroughnesses, ultralocal stresses cross the elasticity line, and plastic deformation of the material begins from crumpling of microasperity tops. A continuous contact area is absent.

At the second stage with an increase in the load the plastic deformation captures groups of ridges, at the same time a mass formation of contact microareas occurs. These microareas, in turn, can be continuous or divided into separate areas depending on the overall surface microgeometry. In some areas plastic deformation may be combined with elastic deformation of the material depending on the shape of asperities, sizes, combination in their location, and, finally, depending on elastic and plastic properties of the material. The third stage is characterized by the beginning of deformation of the microprofile base, at the same time a continuous contact zone of the indenter with the surface occurs, capable of bearing the load without significant plastic deformations.

After treatment with an ultrasonic tool the surface of all samples appeared to be a homogeneous smooth microrelief with the roughness value R_z of 3.5÷5.5 micron, almost no different from each other. The carried out detailed study of the profilogram of the sample made of titanium alloy of the brand VT6 (sample number 2, Table 1) after ultrasonic treatment proves the suggestion that the greatest effect of ultrasonic treatment is achieved on roughness ridges, and in the underlying areas it is significantly smaller. Thus, Fig. 2 clearly shows residual depressions of roughness ridges obtained during mechanical treatment which did not undergo any changes during the ultrasonic treatment. All this indicates that a deformation zone of the first kind occurs, which due to the low penetration of the tool into the detail leads only to partial smoothing of the roughnesses. Contact of the tool with the workpiece in this case has an intermittent nature. The mean microhardness value of titanium alloy VT1-0 is 2400 MPa [4]. Microhardness measurements of titanium alloy VT1-0 samples which had undergone ultrasonic treatment have shown that there is a significant spread in its mean value in the range of values from 3200 MPa up to 4000 MPa. This spread depends on the shape and the size of the roughness relief. A similar situation occurs when measuring the microhardness of titanium alloy VT6 samples.

The analysis of profilograms of titanium alloy VT1-0 samples has shown that a regular microrelief of the surface with the roughness value from $Rz = 5$ microns up to $Rz = 100$ microns occurs as a result of mechanical treatment, consisting of successively located ridges and roots of a certain height at a constant pitch (Fig. 2). The regularity of the profile is of great importance in formation of hardened surfaces because it provides the consistency of properties of the treated surface throughout the entire area of the contact.

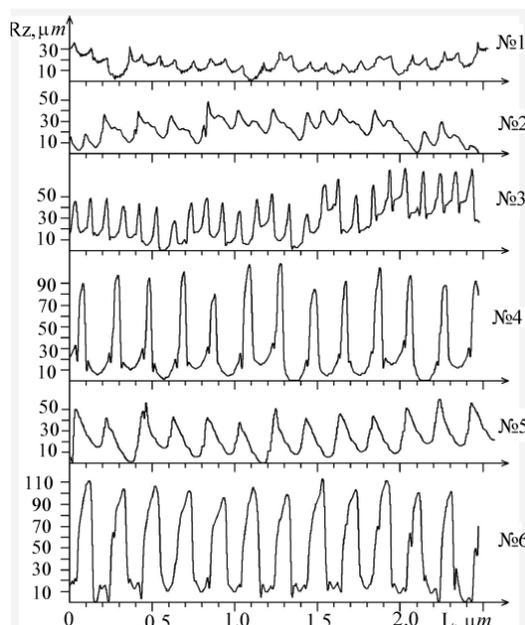


Figure 2. Surface profilograms of samples after mechanical treatment of the alloy VT 1-0

The analysis of profilograms of titanium alloy VT1-0 samples has shown that a regular microrelief of the surface with the roughness value from $Rz = 5$ microns up to $Rz = 100$ microns occurs as a result of mechanical treatment, consisting of successively located ridges and roots of a certain height at a constant pitch (Fig. 3). The regularity of the profile is of great importance in formation of hardened surfaces because it provides the consistency of properties of the treated surface throughout the entire area of the contact.

It has been established that the microrelief of the surface of titanium alloy VT6 samples obtained under same modes of mechanical treatment has a considerably lower surface roughness as compared to samples of titanium alloy VT 1-0. This can be explained by the fact that with a decrease in the plasticity the metal deforms less, the build-up reduces, vibrations reduce and, as a result, the cleanliness level of the treated surface increases.

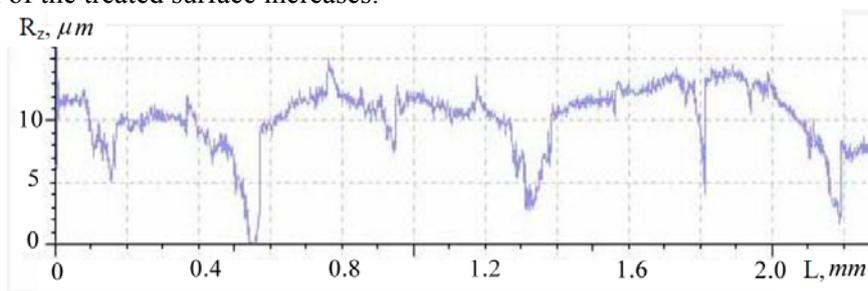


Figure 3. The surface profilogram of the sample of titanium alloy VT6 after ultrasonic treatment

Fig. 4 presents the results of microhardness studies $H\mu$ of titanium alloys from the initial surface roughness. The analysis of these dependencies taking into account a considerable spread of values $H\mu$

allows to draw a conclusion that an increase in the surface roughness results in an increase in the microhardness. This leads to the fact that samples with the highest initial roughness have the greatest increase in surface microhardness values.

To study the microhardness distribution along the depth of the sample the transversal metallographic sections were prepared. Samples of each brand of the titanium alloy with the highest microhardness were subjected to the study.

The analysis of the obtained data for titanium alloy VT 1-0 has allowed to establish that ultrasonic treatment of the surface layer leads to a gradient increase in microhardness values from the initial 2400 MPa up to 4000 MPa on its surface. The value of the transitional zone has amounted to nearly 120 microns (Fig. 5).

The study of the sample of titanium alloy VT6 has revealed that ultrasonic modification of the surface layer leads to a gradient increase in microhardness values from the initial 4000 MPa up to 5400 MPa on its surface. Despite the fact that during treatment of titanium alloy VT6 the hardening effect from ultrasonic treatment is somewhat smaller and amounts to 1400 MPa the value of the transitional zone, wherein a monotonous decrease in the microhardness is observed, is considerably smaller and is about 40 microns.

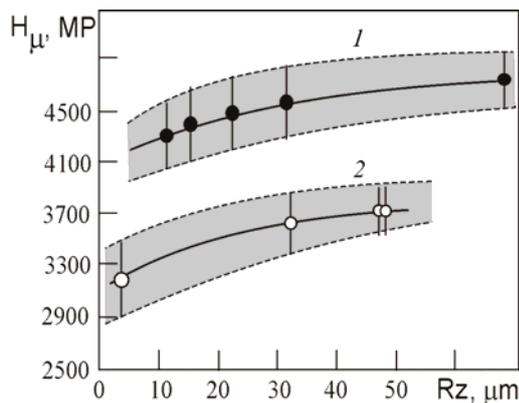


Figure 4. The dependence of the microhardness on the roughness of alloys VT6 (curve 1) and VT1-0 (curve 2). Gray color indicates the area of changes in the microhardness taking into account the measurement error

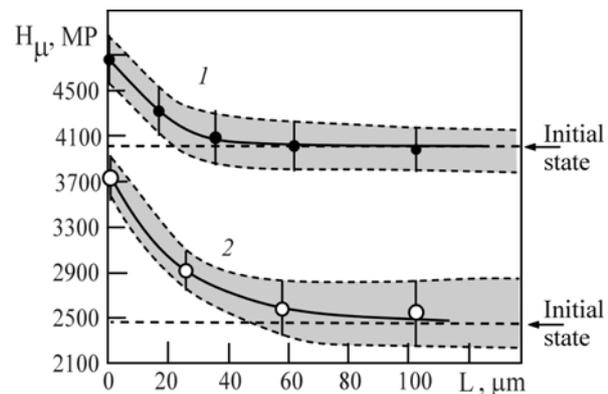


Figure 5. Distribution of the microhardness along the depth from the sonicated surface: 1 – VT6; 2 – VT1-0. Gray color indicates the area of changes in the microhardness taking into account the measurement error

Metallographic studies of the structure of the surface layer of titanium alloy VT1-0 after mechanical treatment have shown that mechanical treatment of the surface leads to formation of a defect structure. The micrograph (Fig. 6) shows that grains are elongated in the direction of the cutting tool movement. Here, grains repeat the contour of the roughness ridge formed by the cutting tool.

Studies of the structure of the surface layer of titanium alloy VT1-0 after ultrasonic treatment have shown its strong refinement with the texture, also directed towards the longitudinal feed of the indenter movement. The value of this surface layer and the refined structure is about 100 microns. As a result of the study of the structure of the surface layer of titanium alloy VT1-0 after sonication it has been found that the surface layer of the sample has a profoundly refined structure with a texture also directed towards the longitudinal feed of the indenter movement. This indicates that the structure has undergone significant changes as a result of the ultrasonic treatment. The degree of refinement of the grain structure is quite substantial, as evidenced by the photomicrographs (Fig. 6).

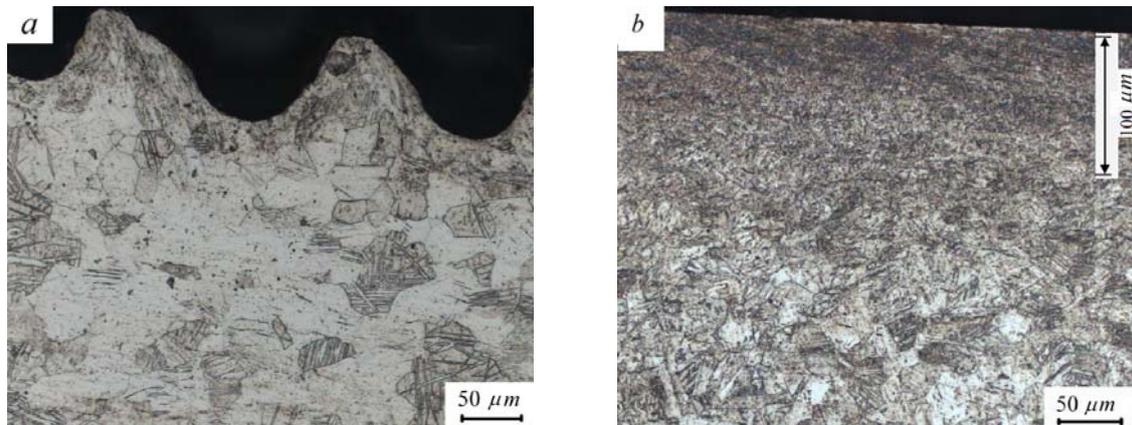


Figure 6. The metallographic image of the surface of titanium alloy VT1-0 after mechanical treatment (a) and after the subsequent ultrasonic treatment (b)

Electron-microscopic studies of samples made of titanium alloy VT1-0 with the highest microhardness have allowed to establish that sonicated surfaces have a heterogeneous microstructure in terms of the volume. The average size of structure elements on the surface of the sample are about 100 nm. At a distance from the surface the average size of structure elements increases up to 200 nm with a further increase up to a regular coarse-grained state.

Similar electron-microscopic studies of sonicated samples of titanium alloy VT6 with the highest microhardness have shown that the microstructure is also heterogeneous in terms of the volume of the near-surface region. The average size of structure elements on the surface of the sample on average is equal to 50 nm. At a distance from the surface the average size of structure elements increases up to 120 nm with a subsequent increase up to a regular coarse-grained state.

Conclusion

1. The existence of the dependence between the initial surface roughness of titanium alloys and the microhardness after ultrasonic treatment has been established. The microhardness of titanium alloys after ultrasonic treatment increases with an increase in the initial surface roughness.

2. It has been shown that an increase in the initial surface roughness of titanium alloys up to 80 microns allows, as a result of ultrasonic treatment, to form in the surface layer a structure with an average size of elements of 100 nm for titanium alloy VT1-0 and 50 nm for titanium alloy VT6.

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