Study of the radial shear rolling effect on the gradient microstructure formation in technical titanium and mechanical properties changes

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Abstract: *The work is devoted to experimental studies of the influence of radial shear rolling on the microstructure evolution of the VT-1 titanium alloy and its gradient distribution over the cross section, as well as changes in mechanical properties. In the course of the conducted studies, two different types of microstructure were obtained. At the periphery of the bar near the surface, a relatively equiaxed ultrafine-grained structure with a grain size of 300-600 nm was obtained, while in the axial zone of the bar, an oriented striped texture was obtained. The resulting structure difference of the peripheral and central zones indicates the gradient nature of the structure distribution. This type of distribution is confirmed by the results of the microhardness study over the cross section of a bar rolled to a diameter of 15 mm. The ultimate strength after deformation increased by 58%, while the elongation decreased by 15%.*
Keywords: *RADIAL SHEAR ROLLING, GRADIENT MICROSTRUCTURE, TECHNICAL TITANIUM, MECHANICAL PROPERTIES.*

1. Introduction

The achievements of modern medicine in the field of implantation are impossible without the productive joint work of scientists, doctors themselves and technical specialists of various specialties, including materials scientists. It was their joint work that made it possible to achieve a long stay in the human body of various implantation materials and structures made of them: rods and plates for connecting damaged bone structures; dentures; endoprostheses and others. But, despite the existing achievements in this direction, there are still problems and questions in the field of development and application of modern materials for implantation. Therefore, the development of both new biocompatible implantation materials and technology for the formation of enhanced, and sometimes unique, properties already in known biocompatible materials is still an urgent direction. At the same time, special attention should be paid to the development of technology for producing long-length products from biocompatible materials with an increased level of mechanical properties.

One of the main and most commonly used methods for increasing the mechanical properties of both ferrous and non-ferrous metals and alloys for more than a decade is the grinding of the structure of these materials to an ultra-fine-grained, and preferably to a nanostructured state [1]. However, for most materials, the growth of strength properties in ultrafine-grained materials is accompanied by an inevitable decrease in its plastic properties, and as a result, such a material becomes brittle and is subject to destruction during stretching. The solution of this problem prompted scientists to develop a new direction in the field of obtaining new materials – the creation of (functional) gradient materials [2]. One of the main features of such materials is the anisotropy of their properties in a given direction, and this is achieved most often by the formation of appropriate structures. The authors of [3-6] have proved that the production of metallic materials with a gradient structure (the coarse-grained state of the metal in the central part of the workpiece, smoothly growing to an ultra-fine-grained state on the surface) is an effective way to increase the plasticity, not of the metal itself, but of metal products as a whole.

It has long been proved that one of the promising and less expensive methods of obtaining ultrafine-grained materials is severe plastic deformation (SPD) [7-8], which can be implemented in metal in various ways [9-13], including the so-called radial shear rolling [14], which just has prospects for obtaining precisely gradient ultrafine-grained materials. This is due to the fact that in the deformation focus during radial shear rolling, a stress-strain state scheme is implemented, which is very close to the all-round compression scheme with large shear deformations. Radial shear rolling also has its own features:

- nonmonotonicity and turbulence of deformation;
- different plastic flow of metal due to the trajectory-velocity features of the process and, as a consequence, different elaboration of the structure of different zones of the workpiece.

2. Experimental part

Due to the peculiarities of the metal flow during radial shear rolling, intense shear deformations are localized in the annular cross-sectional area characteristic of the three-roll scheme. At the same time, in the outer layer of the deformable workpiece, each small trajectory-oriented element undergoes compression deformation along its radius and in the direction of outflow (along the helical trajectory), and stretching deformation across the helical trajectory [15]. It should also be noted that during radial-shear rolling, a constant gradient of velocities and directions of flow along the radius is observed, which also adds additional shear elements to the overall complex picture of the stress-strain state. During such processing, the elements of the structural structure of the metal subjected to an expanding flow with a two-sided sediment (along the trajectory and along the radius) take the form of isotropic isolated particles of high dispersion [15].

As it is known, titanium has biocompatible properties, therefore, the purpose of this work is to study the effect of radial shear rolling on the possibility of forming a gradient structure in it and an increased level of mechanical properties.

The experiment was carried out on the SVP-08 radial shear rolling mill, which is designed for hot deformation of bars of solid circular cross-section made of various metal (ferrous and non-ferrous metals and alloys) and composite materials. VT-1 titanium rods (0.08% C; up to 0.25% Fe; up to 0.07% C; up to 0.1% Si; up to 0.04% N; up to 0.2% O, 99.24-99.7% Ti) with an initial diameter of 30 mm were used as initial blanks. The choice of this grade of titanium is due to the fact that it has mechanical properties commensurate with the mechanical properties of non-rusting steels, and titanium alloying and heat treatment of alloys based on it can achieve the strength level of high-strength steels. Based on the recommendations of works [16-17], titanium rods were rolled on a radial shear rolling mill at a temperature equal to 500 ° C. At the same time, rolling was carried out to the final diameter of 15 mm in stages, i.e. in 5 passes, with compression of 3 mm in each pass. After the 5th pass, the bars were subjected to intensive cooling with water. The bars were also subjected to intensive cooling with water after each pass, which were intended not for further deformation, but for studying the evolution of the microstructure and changes in mechanical properties.

3. Results and discussion

After rolling and cooling, cylinders with a length of 30 mm were cut out of rods of various diameters (from 27 to 15 mm), as well as the original rod. After that, samples for mechanical tests, microhardness measurements and microstructure studies on a transmission electron microscope were cut into strips of 0.3×3×30 mm in size along these cylinders on a high-precision AccuTom-5 cutting machine. Subsequently, samples for microstructure research on a transmission electron microscope JEM-2100 (JEOL, Japan) at an accelerating voltage of 200 kV were subjected to electrolytic thinning on a TenuPol-5 installation to obtain a thin foil from the peripheral and axial zones of the rod along the rolling direction. The most characteristic view of the microstructure of both parts of the rod is shown in Figure 1.

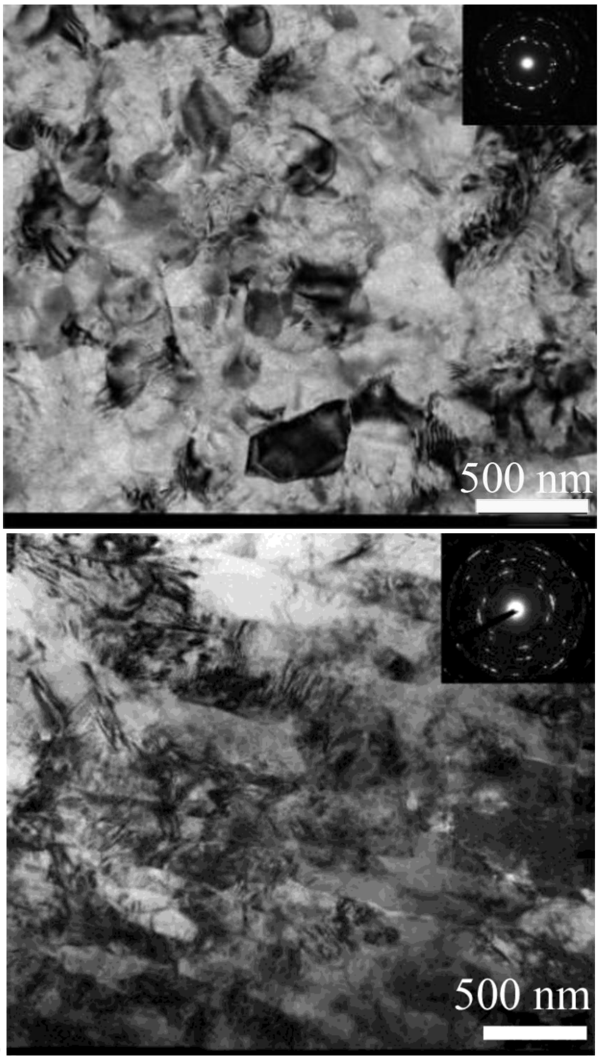

Fig. 1. Titanium structure after radial shear rolling up to a diameter of 15 mm and cooling in water: a - peripheral part of the bar; central part of the bar

Metallographic analysis showed that technical titanium of the VT-1 brand in its initial state has a coarse-grained structure with an average grain size of 70-80 microns. As expected, the microstructure of the peripheral and axial zones after radial shear rolling up to a diameter of 15 mm was not the same. Thus, in the peripheral region of the rod, the microstructure is represented to a greater extent by equiaxed ultrafine grains of 300-600 nm in size, which have high misorientation angles, which is established by the diffraction pattern. The microstructure of the axial zone of the rods after deformation on the radial shear rolling mill is represented by long and narrow grains elongated in the direction of rolling, that is, it is a fibrous texture. The diffraction pattern also confirms the small angles of grain misorientation. That is, as a result, in the peripheral part of the rod, where shear deformation with high turbulence of the metal flow prevailed, we have an equiaxial ultrafine-grained structure, and in the axial zone, where the metal flow had a laminar character along the rolling axis, we have an elongated, oriented structure, resembling the texture of rolling.

Tensile tests carried out on the Instron-1195 testing machine (ITW Inc., USA) showed that the tensile strength after radial shear rolling increased from 704 MPa to 1215 MPa, which is 58%, and the elongation after the fifth pass decreased from the initial 26% to 11%. The values of the tensile strength and relative elongation averaged after each pass (according to the results of 3 experiments with each degree of compression) are shown in Figure 2.

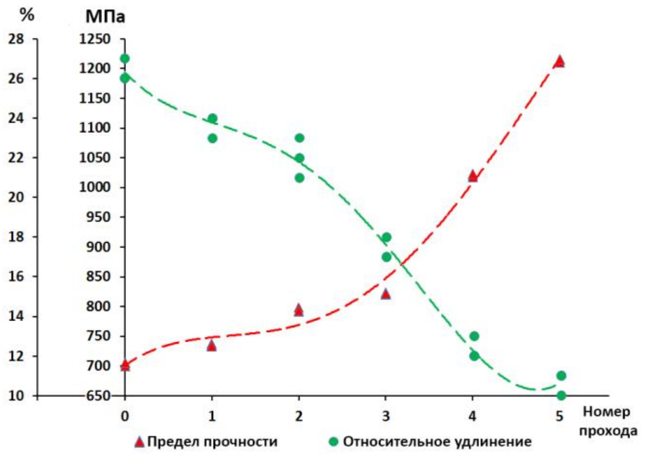

Fig. 2. Change in the tensile strength and elongation of titanium grade VT-1 after radial shear rolling by passes

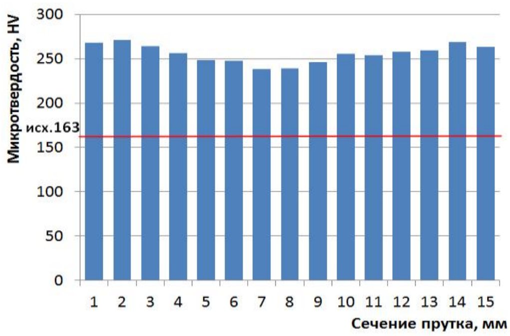

Fig. 3. Change in microhardness of titanium grade VT-1 along the cross section of the bar after radial shear rolling up to a diameter of 15 mm

Taking into account the heterogeneity of the resulting microstructure, microhardness was measured by the cross section of a titanium rod rolled to a diameter of 15 mm on the HVS-1000B microhardness meter (Winex Instrument, UK), which allowed us to construct the microhardness profile shown in Figure 3. Microhardness measurement was carried out by Vickers with a force of 9.87 N at a shutter speed of 15 seconds. The microhardness profile was constructed based on the results of measurements at 15 consecutive points located 1 mm apart.

After radial-shear rolling of a titanium bar to a diameter of 15 mm, the initial microhardness level rose from a value of 163 RM to 238-271 RM, i.e. on average by 60%. At the same time, due to the structural heterogeneity in the cross-section of the bar after rolling, the expected gradual decrease in the microhardness level in the central part by 12.4% relative to the periphery of the part of the bar is observed.

Conclusion

In the course of the conducted research on the deformation of rods made of technical titanium of the VT-1 brand on a radial shear rolling mill, a microstructure of two different types was obtained in them. Thus, a relatively equiaxed ultrafine-grained structure with a grain size of 300-600 nm was obtained at the periphery of the rod, while an oriented, striped texture was obtained in the central zone of the rod. The discrepancy in the structure of the peripheral and central zones of titanium alloy rods formed on the SVP-08 radial shear rolling mill indicates the gradient nature of the structure formed in the resulting rods. This was also confirmed by the results of measuring and constructing a micro-hardness profile along the cross section of a bar rolled up to a diameter of 15 mm. A significant change in the initial microstructure of the titanium rod led to a significant increase in the tensile strength of this rod (by 58% after drawing equal to 4) and a decrease in the plastic characteristic (elongation) with this drawing from 26% to 11%. At the same time, there was a systematic increase in strength characteristics and a decrease in plastic characteristics after each deformation cycle.

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