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CREEP OF VT1-0 TITANIUM ALLOY IN DIFFERENT STRUCTURE STATES AFTER IRRADIATION WITH HELIUM IONS

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The effect of irradiation with helium ions at T = 350°C with an energy of 20 keV and a dose of $1.5\cdot10^{18}$ He/cm^2 on the structure and properties of VT1-0 titanium alloy in the initial and nanostructural states was studied. It has been shown that irradiation of VT1-0 samples in the initial state leads to a decrease in mechanical properties when tested under creep conditions at T = 350 °C, which may be due to dynamic recovery. A material in a nanostructured state is characterized by an increase in strength and creep rate at a test temperature of T = 350°C, while maintaining a plasticity reserve. The effect is associated with the structure rearrangement, grain growth and the development of strain hardening processes as the effective stress increases.

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INTRODUCTION

Currently, titanium is in demand in various industries, including nuclear energy. The technical basis for the use of titanium alloys as structural materials for nuclear power are: high strength, high radiation resistance at operating temperatures (250...400 °C), corrosion resistance in active environments [1]. Low-doped titanium alloys are more than an order of magnitude superior to iron- and chromium-based alloys in terms of the level of induced activity [2]. Titanium alloys retain high plasticity after neutron irradiation and have a low rate of its decrease from neutron fluence. According to these characteristics, they are superior to both low-doped and austenitic steels [3].

Nuclear reactions in materials lead to the appearance of gaseous impurities (helium, hydrogen), which contribute to the manifestation of helium embrittlement, hydrogen embrittlement and gas swellingю

The influence of helium on the properties of functional materials of nuclear and thermonuclear reactors has made it a special problem in the physics of radiation damage and radiation materials science. This led to intensive study of the behavior of helium in various metals and alloys and, accordingly, to a large number of publications on this topic.

There is evidence that helium affects the development of the microstructure of a material at a low level of damage, when the density of dislocations, precipitates and cavities is not yet high. It is known that low solubility leads to the formation of helium clusters and bubbles, which can migrate in the material through the mechanisms of superficial, volumetric, and mixed diffusion [3-5].

Our previous works have shown that the use of IPD ensures the formation of structures in the nanometer range in HCP metals (Ti, Zr) and alloys (VT1-0, BT6, Zr1Nb, Zr-2.5Nb) [6–12]. The study of radiation effects in such materials is of both scientific and applied interest.

The purpose of the work is to study the laws of creep and the evolution of the structure of commercially pure titanium VT1-0, obtained by the intensive plastic deformation (IPD) method, and the effect of irradiation with helium ions on its mechanical characteristics.

MATERIAL AND EXPERIMENTAL PROCEDURE

Studied technical titanium of grade VT1-0 of industrial processing (hot rolled), the impurity content was no more than 0.3%. In order to study the effect of IPD and irradiation by helium ions on the structure and properties of the alloy, the treatments were used in the following modes:

1. MO-1 – industrial processing, initial state;
2. MO-2 – MO-1 + irradiation with He ions with an energy of 20 keV;
3. MO-3 – MO-1 + rolling at 20 °C, deformation (ε) was ε = 3.0;
4. MO-4 – MO-3 + irradiation with He ions with energy 20 keV.

Ion irradiation was carried out at a temperature of ~ 350 °C, close to the operating temperature of the reactor vessel of the VVET 1000 type, according to the method described in [13].

The total absorption dose was $1.5\cdot10^{18}$ He/cm^2. The thickness of the surface layer when irradiated with helium ions with an energy of 20 keV does not exceed 150 nm. Samples of VT1-0 alloy with a thickness of 0.3 mm were processed on both sides. Thus, taking into account the long-range effect (propagation of the shock wave deep into the sample), the influence of irradiation on the structure-sensitive properties can be significant.

Creep tests were carried out in the step loading regime at a temperature of 350 °C, the measurement of elongation accuracy was ~ $5\cdot10^{-5}$ cm. To study the defective structure of the VT1-0 alloy, the method of measuring electrical resistance was used after each treatment. The electrical resistance (R) was measured at room temperature by the compensation method. The structure evolution control was carried out using the electron microscopic method.

RESULTS AND DISCUSSION

Fig. 1 shows the dependences of the creep rate at T = 350 °C for samples of the VT1-0 alloy after various treatments over the entire studied stress range.

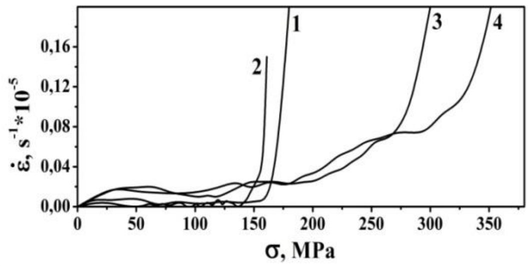

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Fig. 1. Creep rates at 350 °C as a function of the true stress for the samples of VT1-0 alloy subjected to different treatments:
1 – MT-1; 2 – MT-2; 3 – MT-3; 4 – MT-4

Analysis of the results obtained shows that the alloy in the nanostructured state (MO-3) has higher (~2 times) strength characteristics compared to the initial state at the test temperature T = 350 °C, which was noted earlier in our articles [8, 14].

It should be noted that the creep rate of nanostructured samples of the VT1-0 alloy increases compared to the initial state and steps are observed in the dependence of this characteristic on the true stress, which indicates a change in the deformation mechanism as the stress increases (see Fig. 1, curves 3, 4).

It was previously shown [8, 14] that the plastic flow of nanostructured materials is due to the combined action of several mechanisms: intragranular slip of dislocations, cross slip, climbing and annihilation of dislocations at grain boundaries, as well as diffusion creep and slip of the grain boundaries. The contribution of each of these mechanisms to the deformation of the material depends on the test temperature, the level of internal stresses, and the state of the grain boundaries.

After irradiation with helium ions, the strength characteristics of VT1-0 in the initial state (MO-2) decreased by ~ 20 % (Table, Fig. 1), but the plasticity did not change.

Tests under creep conditions of the nanostructured VT1-0 alloy after irradiation showed that the values of the yield strength and plasticity of the samples practically did not change, and the tensile strength increased (see Fig. 1, Table), which indicates the strengthening of the material.

After each treatment, the values of the relative electrical resistance ($R_{300\,K}/R_{77\,K}$) of the samples were determined, which made it possible to monitor changes in the defective state of the material. The results of measuring $R_{300\,K}/R_{77\,K}$ are shown in Table. Data on changes in the value of residual electrical resistance confirm the creep data and indicate a decrease in the defectiveness of the material after treatment with MO-2 and an increase after treatment with MO-4.

Mechanical characteristics and value of residual electrical resistance of VT1-0 alloy after various treatments

Modes of treatment	R_{300}/R_{77}	$\sigma_{0.2}$, MPa	σ_B, MPa	δ, %
MT-1	3.193	18.2	20.6	3.9
MT-2	3.073	14.4	16.1	4.0
MT-3	2.654	19.3	30.0	19.2
MT-4	2.929	19.1	37.6	20.4

Transmission electron microscopy studies of the original samples showed the following.

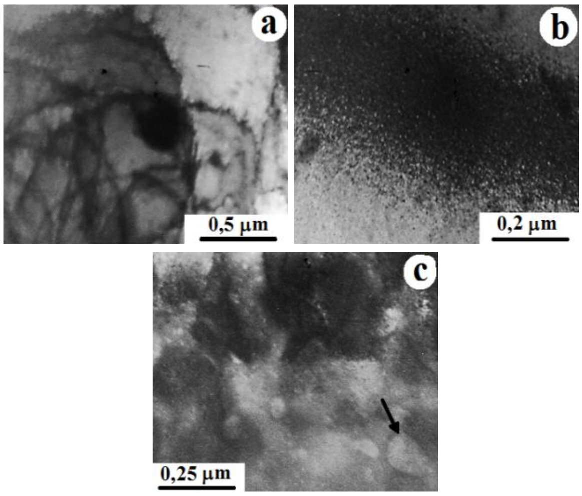

Fig. 2. The evolution of the structure of the BT1-0 alloy during the implantation of helium ions as the dose grows: a – bending deformation of the lattice; b – the emergence of helium bubbles (dose 10^{16} He/cm^2); c – helium bubbles growth (dose $1.5 \cdot 10^{18}$ He/cm^2)

Extended contours in bright-field images (Fig. 2,a) indicate elastic bending of the crystal lattice, resulting from the collective synchronous shift of atoms in the directions of easy shear. Elastic distortions partially relax through the formation of walls of dislocations of the same sign.

The next change in the structure of the surface layer is the nucleation and growth of so-called helium bubbles (pores) of already bulk defects, leading to degradation of properties (see Fig. 2,b and c). Extended elastically deformed regions of the crystal lattice initiate diffusion flows of embedded He atoms with the formation of clusters, and subsequently pores (see Fig. 2,b). These volumetric defects are powerful sinks for interstitial atoms, which causes an increase in the volume of these pores (see Fig. 2,c). At the same time, the level of internal stresses decreases somewhat, which can explain the softening during creep.

Scanning reflection microscopy showed that after ion treatment, a characteristic relief was formed on the polished surface of the samples, grain boundaries were identified (grain size is 1…2 μm), which indicates the rheology of the material (Fig. 3). In addition, places of surface destruction are visible, which are associated with the “exit” of bubbles.

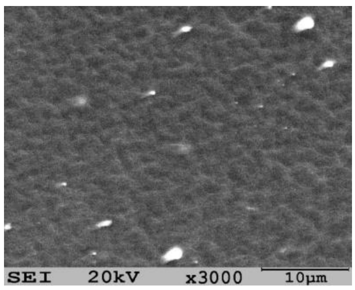

Fig. 3. Surface structure of the VT1-0 alloy after implantation of helium ions. Helium bubbles are visible

Dislocation hardening and structural changes as a result of irradiation led to an increase in microhardness H_μ, measured at 20 °C. The average value of H_μ varies from 1790 MPa in the initial state to 2210 MPa in the irradiated state.

However, creep tests at 350 °C showed softening of the original alloy subjected to ion irradiation. This effect can be associated with dynamic recovery up to recrystallization at $T_{test} \sim 0.38T_{melt}$. At the same time, the plasticity of the material did not change, which may be a consequence of the strong heterogeneity of the recrystallized structure.

In the nanostructured state, as mentioned above, strengthening of the material during creep at 350 °C is observed, which may be associated with restructuring of the structure. Previous studies [8] showed that during creep at 350 °C, the deformation nanostructure of the VT1-0 alloy is destroyed due to the development of recrystallization processes and in place of the nanostructure, a recrystallized structure with an average grain size of ~ 1 μm is formed.

During irradiation with helium ions at 350 °C, the deformation structure is reconstructed. As noted above, due to recrystallization, grains with a size of ~ 2 μm were formed.

During the creep process at 350 °C, the development of recrystallization processes continues, the grains become larger and plastic flow can develop due to intragranular dislocation slip. Analysis of the thermal activation parameters of plastic deformation of nanostructured samples of the VT1-0 alloy shows that the activation volume decreases with increasing stress. Consequently, during the creep process, the density of deformation defects increases with increasing stress and the deformation at the stage of developed plastic flow is controlled by the mechanism of strain hardening, which leads to an increase in the ultimate strength.

The development of strengthening processes during creep of the nanostructured VT1-0 alloy after irradiation with helium ions can also be associated with the removal of type 1 compressive stresses resulting from cold rolling.

The influence of implanted helium is practically not manifested. Helium atoms quickly reach the surface along numerous diffusion ways at high temperatures and tensile loads [15]. Helium bubbles can serve as obstacle in the way of dislocation movement and can influence the manifestation of embrittlement.

CONCLUSIONS

The effect of irradiation with helium ions with an energy of 20 keV and a dose of $1.5 \cdot 10^{18}$ He/cm^2 on the structure and properties of the VT1-0 alloy in the initial and nanostructural states was studied.

Irradiation of VT1-0 alloy samples in the initial state with helium ions with an energy of 20 keV and an accumulated absorption dose of $1.5 \cdot 10^{18}$ He/cm^2 leads to a decrease in mechanical properties when tested under creep conditions at T = 350 °C, which can be associated with dynamic recovery up to recrystallization, which occurs at $T_{test} \sim 0.38\,T_{mel}$. At the same time, the plasticity of the material did not change, which may be a consequence of the strong heterogeneity of the recrystallized structure.

It is shown that at a test temperature of 350 °C, the strength of VT1-0 in the nanostructured state increases by 1.5 times, and the plasticity increases by 5 times, which is due to the development of relaxation processes in grain boundaries and near-boundary regions, as well as recrystallization during creep. This indicates the low thermomechanical stability of the nanostructure formed as a result of intensive plastic deformation.

Irradiation with helium ions at T = 350 °C of samples of the VT1-0 alloy in a nanostructured state leads to an increase in strength and creep rate, while maintaining the plasticity reserve. This may be due to structure restructuring, grain growth, and the development of strain hardening processes as the effective stress increases.

The influence of helium pores and bubbles that appeared during irradiation to a dose of $1.5 \cdot 10^{18}$ He/cm^2 on the mechanical properties of the VT1-0 nanostructured alloy at T = 350 °C against the background of other obstacles in the path of slipping dislocations seems to be insignificant.

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ПОВЗУЧІСТЬ ТИТАНОВОГО СПЛАВУ ВТ1-0 У РІЗНИХ СТРУКТУРНИХ СТАНАХ ПІСЛЯ ОПРОМІНЮВАННЯ ІОНАМИ ГЕЛІЮ

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Вивчено вплив опромінювання іонами гелію з енергією 20 кеВ та дозою $1{,}5\cdot10^{18}$ He/см^2 на структуру та властивості титанового сплаву марки ВТ1-0 у вихідному та наноструктурному станах. Показано, що опромінювання при T = 350 °С зразків ВТ1-0 у вихідному стані призводить до зниження механічних властивостей при випробуваннях в умовах повзучості при T = 350 °С, що можна пов'язати з динамічним поверненням. Для матеріалу в наноструктурному стані характерно підвищення міцності та швидкості повзучості за температури випробування T = 350 °С при збереженні запасу пластичності. Ефект пов'язується з перебудовою структури, зростанням зерен та розвитком процесів деформаційного зміцнення під час підвищення напруги.