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MODIFICATION OF THE PROPERTIES OF VT1-0 NANOSTRUCTURED TITANIUM ALLOY USING VARIOUS INFLUENCES

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It was studied effects of electron irradiation (energy E=10 MeV, dose D=5·10^{19} cm^{-2}) and ultrasonic treatment (f=20 kHz, T=300 K, t=30 min) on the evolution of the structure and creep of VT1-0 titanium alloy in two structural states: industrial production and obtained by the method of intensive plastic deformation (IPD). The relationship between the structural states obtained as a result of these effects and the regularities of plastic deformation development during creep was established. It has been shown that at test temperatures of 20 and 350 °C, the strength characteristics of the VT1-0 alloy in the nanostructured state increase by 1.5–2 times compared to the characteristics of the industrial alloy. The created nanostructure is resistant to subsequent deformation under creep conditions at a test temperature of 20 °C and after electron irradiation, as well as ultrasonic treatment, retains high strength properties and has prospects for practical application at temperatures in the region of 20 °C. At test temperature of 350 °C, the deformation nanostructure is destroyed due to the development of recrystallization processes. Electron irradiation and ultrasonic treatment lead to an increase in strength, which is associated with a slowdown in recrystallization processes and the formation of new deformation boundaries (polygonal boundaries, microtwins), which are more resistant to tensile loads. The reason for the hardening may also be the low energy of the stacking fault of the VT1-0 alloy.

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INTRODUCTION

The need to create materials with high radiation resistance and providing the required service life of fuel system cladding is one of the main problems of reactor materials science [1].

The technical basis for the use of titanium alloys as structural materials for nuclear power engineering are: the high strength, the high radiation resistance at operating temperatures (250...400 °C), corrosion resistance in active surroundings [2]. Low-alloy titanium alloys are more than an order of magnitude higher to alloys based on iron and chromium in the level of induced activity [3, 4] and are similar in strength characteristics to traditional structural steels, but are 45 % lighter, however, there are still many questions on the physics of strength.

In this regard, the study of the patterns of nanostructure formation in titanium alloys is of both scientific and practical interest, since nanocrystalline materials have unique mechanical properties such as high strength, wear resistance, hardness, and high fatigue properties. No less important is obtaining an idea of the nature of changes in nanostructures and the properties of the nanocrystalline state as a result of external influences.

To obtain nano- and submicrocrystalline structures in titanium alloys, cryogenic intensive plastic deformation (IPD) methods such as quasi-hydroextrusion [5], forging [6] and rolling [7, 8] at cryogenic temperatures are used.

Nanocrystalline metals and alloys obtained by IPD methods have higher functional and mechanical properties due to a number of structural features [9]. Of particular importance is the large proportion of grain boundaries in the structure of nanocrystalline materials, which are in a nonequilibrium state and have an increased free volume. Such boundaries create a high level of internal stress and, as a consequence, nanomaterials have low plasticity and thermal stability [10, 11], which worsens their manufacturability.

In [12, 13] a number of methods and physical mechanisms of influence by various physical fields by activating relaxation processes, including ultrasonic treatment (UST), are described for the targeted change of the structural state and physical and mechanical properties of structural materials and the formation of a given set of operational characteristics. Subsequently, in works [14–18] it was shown that low-intensity ultrasonic treatment is a promising method for effectively influencing the structural state and properties of structural materials subject to intense plastic deformation.

The properties modification of the studied nanocrystalline and ultrafine metals and alloys with a hcp lattice (Zr [14], Zr1Nb [15, 16], Zr-2.5Nb [17], Hf [18]) is a consequence of the relaxation of the nonequilibrium defect structure. In these materials, ultrasonic treatment reduces the level of internal stresses and levels out their spectrum in the volume of the material while maintaining the size factor and increasing the homogeneity of the structure. For deformed austenitic steel 06Kh16N15M3B, the structural state of the boundaries of the nanometer-sized martensitic phase determines the magnetic and electrical properties and the features of the relaxation processes under ultrasonic exposure [19, 20].

When assessing and selecting materials in mechanical engineering, much attention is paid to the study of creep characteristics, as well as their change under the influence of radiation, temperature, and mechanical loads, since many industrial products operate under static loading conditions.

The imposition of tensile stresses leads to a sharp deduce from the metastable state of the previously created deformation structure, and to the formation of a new structure that adapts to uniaxial loading [21–24]. In addition, an important issue is the stability of the obtained structural states in a wide temperature range, since the strength and plastic characteristics of the material can change significantly in the event of structural instability [23, 24].

The aim of this work is to study the regularities of creep and evolution of the structure of industrial titanium alloy VT1-0 subjected to IPD by rolling, as well as the influence of electron irradiation and ultrasonic treatment on its mechanical characteristics.

MATERIAL AND PROCESSING METHODS

We investigated titanium alloy VT1-0 of industrial production, the amount of impurities of which does not exceed 0.3 %. The samples for testing were made by electric spark cutting in the form of plates with a size of 0.3×3×50 mm. In order to study the effect of electron irradiation on the structure and properties of the VT1-0 alloy, the following processing modes were studied:

1. MT-1 – initial state;
2. MT-2 – MT-1 + electron irradiation;
3. MT-3 – deformation by rolling at 20 °C, strain (ε) was ε = 3.0;
4. MT-4 – MT-3 + electron irradiation;
5. MT-2 – MT-1 + UST at 300 K.

The samples were irradiated with an electron beam with the energy of E = 10 MeV and with the dose set of $D = 5\cdot10^{19}$ cm^{-2}. The electron beam was formed by a linear electron accelerator operating in pulsed mode. The average beam current was 10 μA, the pulse duration was 3.6 μs, the transmission frequency was 6 Hz. The temperature of the samples not exceeding 90 °C and was determined on the temperature dependence of the electrical resistance of the VT1-0 alloy.

The part of strained samples was subjected to low-intensity UST (f = 20 kHz) at T = 300 K by the method described in [17]. The amplitude of the ultrasonic shear stresses was 65 MPa, the duration was 30 min.

For studying the material defect structures, the electrical resistance (R) was measured by 4-th points scheme at T = 300 K after each treatment. A measuring error did not exceed ±0.05%. The structure evolution monitoring was carried out by electron microscopy.

Creep tests were carried out in the step loading regime, the elongation measurement accuracy was $\sim5\cdot10^{5}$cm.

Activation parameters and the level of internal stresses were determined using differential methods described in [25].

RESULTS AND DISCUSSION

Fig. 1 shows the dependences of the creep rate at T = 20 and 350 °C on the true stress of the VT1-0 alloy samples in various structural states.

Analysis of the results obtained shows that IPD (MT-3) leads to an increase in the strength characteristics of the VT1-0 alloy at all test temperatures. In this case, the plasticity of strained samples decreased at 20 °C, i.e. the material has hardened, but at the test temperature T = 350 °C the plasticity increased by 5 times.

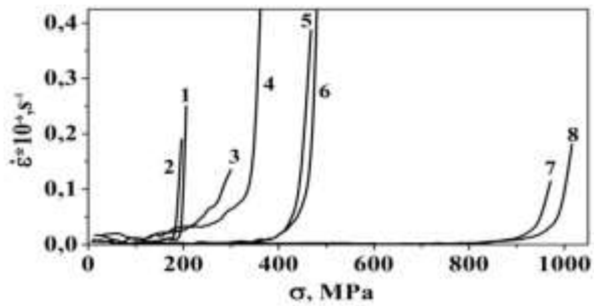

Fig. 1. Creep rates as a function of the applied stress at T = 20 °C (5, 6, 7, 8) and T = 350 °C (1, 2, 3, 4) of VT1-0 alloy specimens after the treatments: MT-1 – 1, 5; MT-2 – 2, 6; MT-3 – 3, 7; MT-4 – 4, 8

After electron irradiation of the VT1-0 alloy in the initial state (MT-2), the strength characteristics at 20 and 350 °C remained unchanged compared to the initial condition (MT-1).

Irradiation by electrons of nanostructured samples weakly effects on its mechanical properties at a test temperature of 20 °C, but reveals a tendency to increase the strength, plasticity and creep rate at the test temperature of 350 °C compared to the characteristics of the unirradiated samples.

It should be noted that the creep rate of irradiated and non-irradiated nanostructured samples of the VT1-0 alloy (MT-3 and MT-4) increases compared to the creep rate of irradiated and non-irradiated undeformed samples (MT-1 and MT-2), and steps are observed on the dependence of the creep rate on the true stress at T = 350 °C, which indicates a change in the deformation mechanism with increasing stress.

Analysis of thermal activation parameters of plastic deformation of nanostructured samples of VT1-0 alloy shows that the density of deformation defects increases with an increase in stress during the creep process. Deformation at the stage of developed plastic flow is controlled by the mechanism of thermally activated overcoming of obstacles by moving dislocations, i.e. by the mechanism of strain hardening, which leads to an increase in the ultimate strength.

The obstacles that control the process of intragrains plastic flow change as the applied stress increases. At the initial stages, these can be point defects and impurities, and with an increase in stress the forest dislocations and dislocation accumulations may be. Simultaneously with the processes of intragrains slipping, recovery processes develop near the grain boundaries and the slip on the boundaries appeared, as well as the rearrangement of the structure at the test temperature T = 350 °C, as evidenced by a sharp increase in the creep rate at stresses near to the ultimate strength.

After deformation by rolling and irradiation, the values of the relative electrical resistance ($R_{300\,K}/R_{77\,K}$) of the VT1-0 alloy samples were determined. Determination of the value of the residual electrical resistance makes it possible to control the changes in the defect state of the material. The measurement have shown that irradiation leads to the decrease in the value of $R_{300\,K}/R_{77\,K}$, which indicates the decrease in the level of internal stresses in the samples of the VT1-0 alloy of initial state and to the increase in internal stresses in the samples of the VT1-0 nanostructured alloy, which is consistent with the changes in the creep characteristics at T = 20 °C.

Structural studies have shown that titanium alloy VT1-0 of industrial production has a very heterogeneous structure. In the body of grains, there are microvolumes with a few dislocations, separate dislocation accumulations, less often with a cellular structure. A feature of the structure can be considered a high concentration of packing defects (Fig. 2,a).

The main consequence of electron irradiation of the initial structure of VT1-0 alloy can be considered the appearance of bending deformations of the crystal lattice and an increase in the width of stacking fault. Elastic distortions are evidenced by extended contours in electron microscopic images, the appearance of which is due to the synchronous displacement of the lattice atoms from the equilibrium positions. Partial relaxation of distortions occurs through the formation of misfit dislocations. They are visible in and along the contours. The reason for the expanding of stacking faults may be the active absorption of the complexes “vacancy – interstitial impurity atom” formed during the irradiation (see Fig. 2,b).

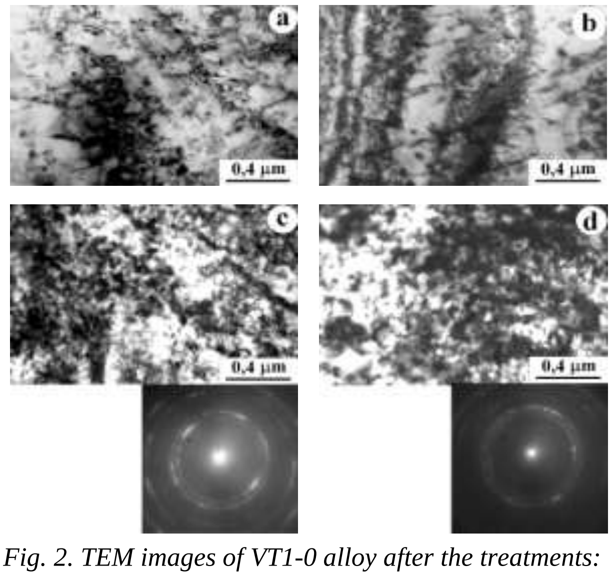

Fig. 2. TEM images of VT1-0 alloy after the treatments: a – MT-1; b – MT-2; c – MT-3; d – MT-4

During deformation, rotational plastic flow modes develop, forming at ε=3.0 the structure with a grain size of 55 to 140 nm. Grains with a size of 100 nm dominate, i.e. in fact, the nanostructure was formed, which is confirmed by the dark-field image on Fig. 2,c. The concentration of the boundary phase reaches a significant magnitude and the width of the boundaries traces in electron microscopic images can be ~25 nm. There are practically no dislocations in the body of grains (see Fig. 2,c).

Irradiation of the nanostructure formed after rolling leads to relaxation of internal stresses both in the boundaries and in the grains themselves. The boundaries are more clearly marked, and the grains were broken into blocks or cells, separated by low-angle dislocation boundaries. The total length of the boundaries of different power increased by 2.5–3 times (see Fig. 2,d), while, as can be seen in the dark-field image, the nanostructure was conserved.

Deformation in the creep regime at T=350 °C of the initial samples is accompanied by the formation of the cellular structure (Fig. 3,a).

In the irradiated initial samples, such a structure does not have the time to form during the creep process. The applied mechanical and thermal energy leads to the emission of dislocations and their partial annihilation (Fig. 3,b).

The superposition of the tensile load in the creep regime at 20 °C on the deformation nanostructure leads to the destruction of most of the boundaries and the formation of a cellular and fragmented structure with a fragment size of 0.05…0.15 µm. New boundaries are formed by dislocations that appeared during the disintegration of unstable deformation boundaries (Fig. 3,c).

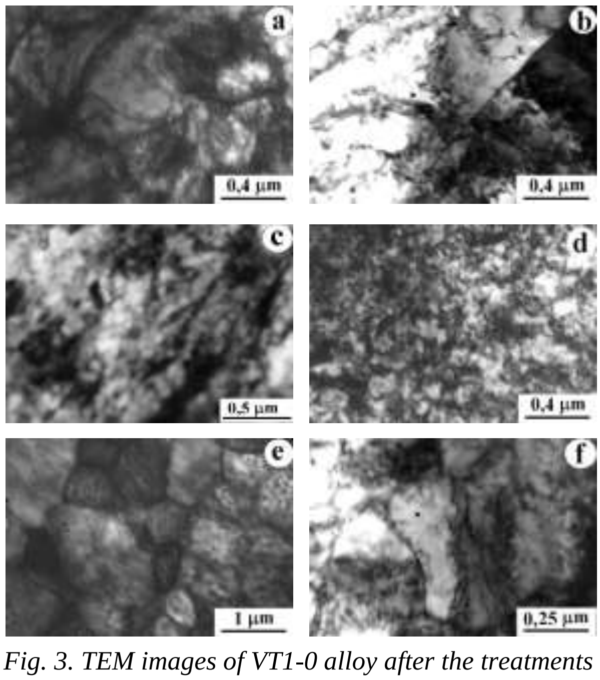

Fig. 3. TEM images of VT1-0 alloy after the treatments and creep (σ~$0.9\sigma_B$): a – MT-1+creep at 350 °C; b – MT-2+creep at 350 °C; c – MT-3+creep at 20 °C; d – MT-4+creep at 20 °C; e – MT-3+creep at 350 °C; f – MT-4+creep at 350 °C

The plastic flow at 20 °C of irradiated nanostructured samples (MT-4) was realized within grain boundaries (see Fig. 3,d). Under conditions of a limited volume of structural elements of deformation, it quickly obtained a collective character, initiating disclination effects in the body of grains. This is evidenced by the comminution of the grains (20…100 nm). The rotations of grains are possible, taking into account the quasi-amorphous state of the boundaries when the limiting concentration of dislocations is obtained with overlapping of their cores. It should be noted that the nanostructure is conserved (see Fig. 3,d).

During creep at 350 °C of strained samples (MT-3), the recrystallized structure with an average grain size of ~ 1 μm was formed in place of the nanostructure (see Fig. 3,e).

Thus, the development of hardening processes during creep may be connected with the fact that the restructuring of the structure begins at an earlier stage of deformation than was observed in [17, 18].

During creep at 350 °C of irradiated nanostructured samples (MT-4), recrystallization was incomplete due to the activation of polygonization processes with the formation of closed and open dislocation boundaries (see Fig. 3,f). This may be due to the fact that the level of internal stresses in the nanostructured material decreased after irradiation.

It is known from theory [20] that the recrystallization process can begin immediately at a sufficiently high level of energy stored in the metal during deformation. At a lower level of internal stresses and lower heating, recovery processes occur, leading to the formation of a polygonal structure. In this case, the energy of the system decreases and the polygonization process can compete with the recrystallization process, delaying it and increasing the temperature of its onset [26].

Thus, irradiation of the nanostructured VT1-0 by electrons with an energy of E = 10 MeV and a dose of $D = 5 \cdot 10^{19}\ cm^{-2}$ leads to the decrease in the level of internal stresses and the slowdown in the transformation processes of the nanostructure in creep conditions.

In order to reduce the level of internal stresses, the influence of ultrasonic action on the regularities of creep and evolution of the structure of technically pure titanium VT1-0 obtained by the IPD method was studied.

Fig. 4 shows the dependences of the creep rate at T = 20 and 350 °C on the true stress of the VT1-0 alloy samples in various structural states.

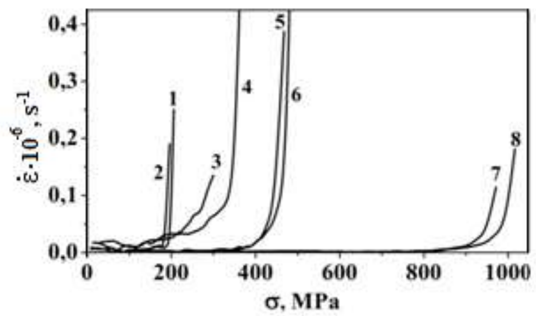

Fig. 4. Creep rates as a function of the stress at T=20 °C (3, 4) and T=350 °C (1, 2) of VT1-0 alloy specimens after the treatments: MT-3 – 1, 3; MT-5 –2, 4

It can be seen, that after ultrasonic treatment of the VT1-0 nanostructures alloy (MT-5), the tensile strength at the test temperature T = 20 °C increased by~8% compared to MO-3, while maintaining the yield strength and plasticity.

At the test temperature T = 350 °C, the tensile strength increases by ~ 20%, while the yield strength and plasticity do not change.

It was shown in [14–17] that, as a result of low-intensity ultrasonic action, the material is softening because of the relaxation of internal stresses in the bulk of the material due to a number of factors. High-frequency alternating action generates a large number of vacancies, which stimulates non-conservative dislocation slip. Moreover, the dissipation of vibration energy occurs mainly at the interfaces, which can lead to the formation of an equilibrium state of the boundaries, as well as to a decrease in the level of local stresses. In this case, the equilibrium grain boundaries are more resistant to subsequent mechanical and thermal effects under creep conditions.

In contrast to the effect of ultrasonic treatment on the properties of nanostructured Zr and Zr1Nb samples [14–17], nanostructured titanium VT1-0 is characterized by an increase in the tensile strength, while maintaining the yield strength and plasticity.

After deformation by rolling and ultrasonic treatment, the values of the relative electrical resistance ($R_{300\ K}/R_{77\ K}$) of samples of the VT1-0 alloy were determined. Determining the value of the residual electrical resistance makes it possible to control the change in the defective state of the material. Studies have shown that ultrasonic treatment leads to an decrease in defectiveness and a decrease in the level of internal stresses in samples of the VT1-0 nanostructure alloy.

The main result of ultrasonic treatment is a significant reduction in the overall level of internal stresses, while maintaining the size factor and increasing the homogeneity of the structure. This is evidenced by the absence of bending contours at the boundaries in bright-field images and the absence of strands between reflections in microdiffraction patterns (Fig. 5,a).

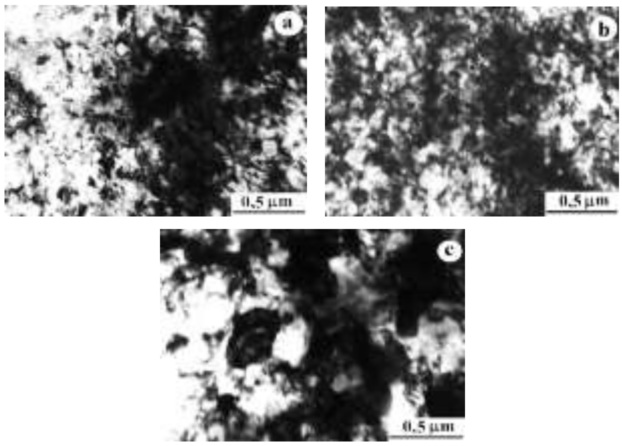

Fig. 5. TEM images of VT1-0 alloy after the treatments: a – MT-5; b – MT-5+creep at T=20 °C (σ~0.9σ_B); c – MT-5+creep at T=350 °C (σ~0.9σ_B)

In the process of creep at T=20 °C in a relaxed structure, the translational modes are realized by the formation of cells in the body of subgrains. The deformation boundaries turn out to be more resistant to tensile loads (Fig. 5,b).

The deformation is localized at the boundaries of nanograins in the form of clusters of dislocations. Microtwins (twin stacking faults) are formed in the body of nanograins, which are typical for cold free deformation, since their formation requires two times less energy than conventional stacking faults. They are additional barriers for slipping dislocations.

Increasing the test temperature in the creep mode to T = 350 °C leads to unfinished primary recrystallization. The size of new grains is about ~ (0.2…1) μm. Polygonal boundaries are observed in the body of some grains (see Fig. 3,c). Deformation is also carried out by developing translational modes. However, an additional reserve of uniform plasticity is achieved due to thermally activated structural rearrangement with the formation and displacement of high-angle and low-angle polygonal boundaries. Recrystallization nuclei are formed at the triple junctions of deformation boundaries – the places of maximum distortion.

Thus, structural studies indicate a decrease in the overall level of internal stresses, which is associated with the development of return processes and the restructuring of the structure.

To determine the mechanisms of deformation during the creep of the VT1-0 nanostructures alloy, the activation volume (V) was measured and calculated by using the formulas of the theory of thermally activated plastic deformation [23]. The obtained value for samples after both treatments (MT-1 and MT-2) is about $V{\sim}1.5{\cdot}10^{-21}$ cm^3 at the stress near the yield point. This allows us to conclude that the process of plastic deformation is controlled by impurities and point defects. As the applied stress increases, the activation volume decreases at all test temperatures.

According to the theory, this means that deformation defects also control the plastic flow of the material, and therefore, the mechanism of strain hardening works [26], or the localization of plastic deformation increases during creep [27]. Since in our case the tensile strength increases, while maintaining the yield strength and plasticity, it can be assumed that both of the above processes can be responsible for the development of deformation during creep.

According to structural studies, in the process of creep of VT1-0, simultaneously with the process of the dislocations slipping, reverse processes develop at the grain boundaries and the structure is rearranged. We have shown [23, 24] that the plastic flow of a nanostructures material obtained by IPD 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 grain boundary slip. 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.

Based on the stress dependence of the creep rate (see Fig. 4), it can be concluded that the contribution to the deformation of the slip mechanisms inside the grains and near the boundaries in VT1-0 specimens after UIT is greater than in the deformed state. Fig. 1 show that the length of the stage of a smooth increase in the creep rate with increasing stress, which corresponds to the development of slip and climbing of the dislocations inside the grains and at boundaries, is longer for specimens after UIT than for specimens not subjected to ultrasonic treatment.

Structural studies also show that a decrease in the level of internal stresses due to UST leads to a slowdown in the processes of recrystallization and the development of polygonization. It is known that at the lower level of internal stresses, a recovery process occurs, leading to the formation of a polygonal structure. In this case, the energy of the system decreases, and the polygonization process can compete with the recrystallization process, delaying it and increasing the stress or temperature level to start it [28]. Thus, at stresses near the ultimate strength ($\sigma \sim 0.9\sigma_B$), the recrystallization is unfinished, i.e. the completely ordered structure has not yet formed and this may to lead to an increase in the tensile strength.

It is interesting that, according to the data on the change in the residual electrical resistance and structural studies, there is a decrease in the overall level of internal stresses in the VT1-0 nanostructures alloy after UST, but the yield strength under creep conditions, i.e. indicator of the magnitude of internal stresses at the macro level, does not change at both test temperatures.

Possibly this means that when we analyzing the results, it is necessary to take into account not only the characteristics of obstacles, changes and rearrangements of the structure, but also the parameters of the dislocation itself, such as its splitting, which is controlled by the stacking fault energy.

It is known [29, 30] that the stacking fault is one of the most common defects in the hcp crystal lattice, and its presence can significantly effect on the processes of plastic deformation, hardening, fracture, recrystallization, the nature of phase transformations, etc. in metallic materials. The stacking fault energy, associated with the features of the electronic structure of the material, determines the magnitude of the splitting of a dislocation, and the magnitude of the splitting effects all processes of dislocation rearrangements [29].

The splitting of dislocations largely controls the mobility of dislocations, their capability to overcome various type of obstacles, the character of direct interaction with other defects, which ultimately determines the level of structurally sensitive properties, primarily mechanical ones [29].

It is known [30] that unsplit and split dislocations interact with point defects in different ways, as a result of which, a decrease in the stacking fault energy can lead to effort in moving point defects to the boundaries of nanograins and slow down the processes of dislocation climbing associated with vacancy flows, which will complicate the process of restoring the structure of boundaries.

Taking this into account, it should be expected that the effect of excess point defect density on mechanical properties will be different in metals with different stacking fault energies, varying from softening to hardening in crystals with a large number of split dislocations, i.e. characterized by low stacking fault energy.

It is known [29], that the stacking fault energy of titanium is ~ 20 mJ/m^2, which is an order of magnitude less than that of Zr (~ 220 mJ/m^2), and therefore the recovery processes and restoring of the boundary structure in these structural materials can proceed differently.

CONCLUSIONS

The effect of 10 MeV electron irradiation of a dose of $D = 5{\cdot}10^{19}$ cm^{-2} and of ultrasonic treatment on the creep at test temperatures of 20 and 350 °C and structure evolution of the samples of VT1-0 titanium alloy of industrial production (initial state) and samples obtained by the IPD method by rolling (nanostructured state) was studied.

It is shown that, at the test temperatures, the strength characteristics of VT1-0 alloy in the nanostructured state increase by 1.5–2 times in comparison with the characteristics none. The deformation nanostructure is resistant to subsequent deformation under creep conditions at the test temperature of 20 °C and is destroyed at the test temperature of 350 °C due to the development of recrystallization processes.

Electron irradiation weakly effects on the mechanical characteristics of the VT1-0 alloy, both initial and nanostructured, during creep at T = 20 °C, but leads to the preservation and stabilization of the nanostructure, which may have good prospects for practical application at temperatures in the region of 20 °C.

Used irradiation by electrons of the VT1-0 alloys in the nanostructured state reveals a tendency to increase the strength, plasticity and creep rate at the test temperature of 350 °C compared to the characteristics of the unirradiated state. This is due to the deceleration in recrystallization processes and the development of polygonization processes due to the decrease in the level of internal stresses in the nanostructured material after irradiation, i.e. the process of structure transformation decelerated in creep conditions.

Studies of creep at T = 20 and 350 °C of nanostructured VT1-0 alloy showed that ultrasonic treatment leads to an increase in tensile strength, while maintaining the yield strength and plasticity. This may be due to the rearrangement of the structure and the formation of new deformation boundaries (cell walls, polygonal boundaries, microtwins), which are more resistant to tensile loads.

In addition, the low stacking fault energy of the VT1-0 alloy can make it effort for point defects to move to the boundaries of nanograins and slow down the recovery processes associated with vacancy flows, which complicates the reconstruction of the structure of boundaries and leads to a slowdown in recrystallization processes and the development of polygonization.

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МОДИФІКАЦІЯ ВЛАСТИВОСТЕЙ НАНОСТРУКТУРНОГО ТИТАНОВОГО СПЛАВУ ВТ1-0 З ВИКОРИСТАННЯМ РІЗНИХ ВПЛИВІВ

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Досліджено вплив електронного опромінення (енергія E=10 МеВ, доза $D=5\cdot10^{19}$ см$^{-2}$) та ультразвукової обробки (f=20 кГц, T=300 K, t=30 хв) на еволюцію структури і повзучість титанового сплаву ВТ1-0 у двох структурних станах: промислового виготовлення та отриманого методом інтенсивної пластичної деформації (ІПД). Встановлено зв'язок між структурними станами, отриманими в результаті цих впливів, із закономірностями розвитку пластичних деформацій при повзучості. Показано, що при температурах випробувань 20 і 350 °C міцнісні характеристики сплаву ВТ1-0 у наноструктурному стані підвищуються в 1.5–2 рази, як порівняти з характеристиками промислового сплаву. Створена наноструктура є стійкою до подальшої деформації в умовах повзучості при T = 20 °C, а після електронного опромінення, а також ультразвукової обробки, зберігає високі властивості міцності та має перспективи практичного застосування при температурах у районі 20 °C. При температурі випробування 350 °C відбувається руйнування деформаційної наноструктури внаслідок розвитку процесів рекристалізації. Електронне опромінення та ультразвукова обробка призводять до підвищення міцності, що пов'язано з уповільненням процесів рекристалізації та утворенням нових меж деформації (полігональних меж, мікродвійників), більш стійких до навантажень розтягу. Причиною зміцнення також може бути низька енергія дефекту упаковки сплаву ВТ1-0.