THE ROLE OF THE PEIERLS RELIEF IN LOW TEMPERATURE PLASTICITY OF THE TI-NB SUBSTITUTIONAL ALPHA SOLID SOLUTION

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Alloying elements, like impurities, significantly influence the physical mechanisms of plastic deformation in pure metals. It is important to consider not only their concentration but also their type, which influences the controlling dislocation mechanisms differently. In this regard, they can be divided into two classes. Interstitial atoms of the solute, located in the interstitial sites of the crystal lattice, typically create large asymmetric deformations and cause more rapid strengthening. On the other hand, substitutional atoms, which cause strengthening as a result of lattice distortion due to a size mismatch with matrix atoms, have a significantly weaker strengthening effect. Previous studies have focused on the influence of solute interstitial atoms on the plasticity mechanism of high-purity Ti, which involves dislocations overcoming Peierls barriers [1]. It has been shown that at oxygen concentrations above 0.2 at.%, the controlling mechanism is thermally activated overcoming of local barriers created by interstitial impurity atoms [2]. In contrast, research on the influence of substitutional atoms on the deformation behavior and low-temperature plasticity mechanisms of solid solutions of hcp metals of this crystallographic group is very limited. However, alloying with chemical elements of this type plays an important role in determining the chemical and physicomechanical properties of modern Ti alloys [3].

Experimental procedures

We studied titanium alloys with a concentration of 0.25, 1.05 and 2.1 at. % Nb which alpha-substitutional solid solutions. High purity Ti and Nb electron beam melting were used to produce the alloys. The samples had the form of double-sided blades with a working cylindrical blade with diameter of 2 mm and length of 12 mm. After annealing in a vacuum $7\cdot10^{-4}$ Pa during one hour at the temperature of 973 K, the average grain diameter in the samples was $d = 35$ µm (measured metallographically). Mechanical characteristics in the temperature range 1.7 – 420 K were determined in experiments on quasi-static uniaxial tension with a strain rate of $\acute{\varepsilon} = 5 \times 10^{-4}$ s^{-1}. In the case of uniaxial tension of polycrystalline samples, the maximum shear stress with respect to the tension axis $\tau_0 = 0{,}5\,\sigma_0$ was taken τ_0.

Results and discussion

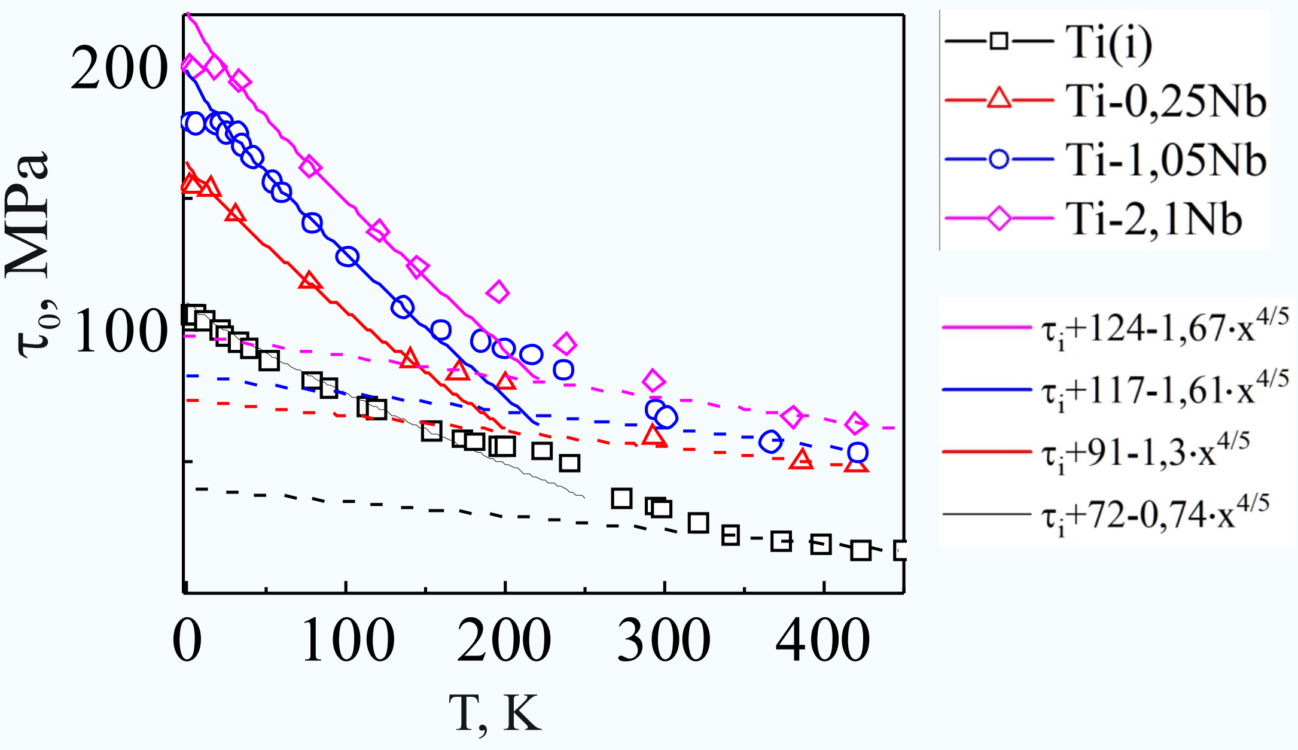

Fig. 1. Temperature dependence of the yield strength $\boldsymbol{\tau_0}$ *of α-solid solution Ti-Nb with a concentration. The symbols – the experimental results, and the solid lines – the theoretical dependences according to Eq. 6 for the parameters given in Table 2. The dotted line indicates the level of internal stresses i 423 K [G(T)/G(423 K)].*

In Fig. 1 shows in the temperature range above the threshold ***Ta***, which corresponds to the transition from the low temperature athermal plasticity regime to the thermally activated one, two regions with a monotonic decrease in the yield strength upon heating of the sample are observed. They are separated by a feature such as a diffuse fracture in the vicinity of 200 K. At temperatures above 400 K, the sensitivity of the shear stress to temperature changes decreases significantly and becomes close to the temperature dependence of the shear modulus ***G(T)***.

The strain rate sensitivity $S = (\triangle\tau/\triangle\ln\acute{\varepsilon})_T$ (Fig. 2) dependences are typical for thermally activated plastic deformation of most metals, then at lower temperatures the ***S*** value decreases sharply and reaches practically zero at T = 4 – 18 K, indicating a change in the plasticity regime.

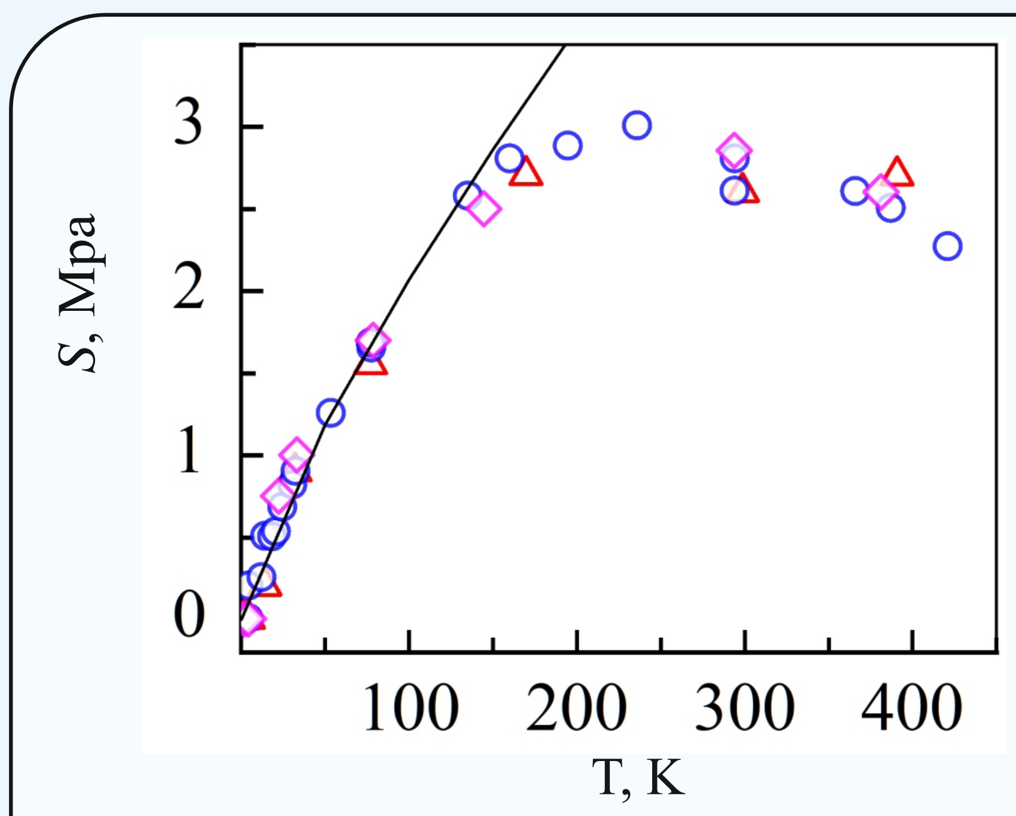

Fig. 2. Temperature dependence of the strain rate sensitivity $S = (\triangle\tau/\triangle\ln\acute{\varepsilon})_T$ *of α-Ti-Nb alloys. The solid curve shows the theoretical dependence of Eq. 7 for the parameters given in Table 2.*

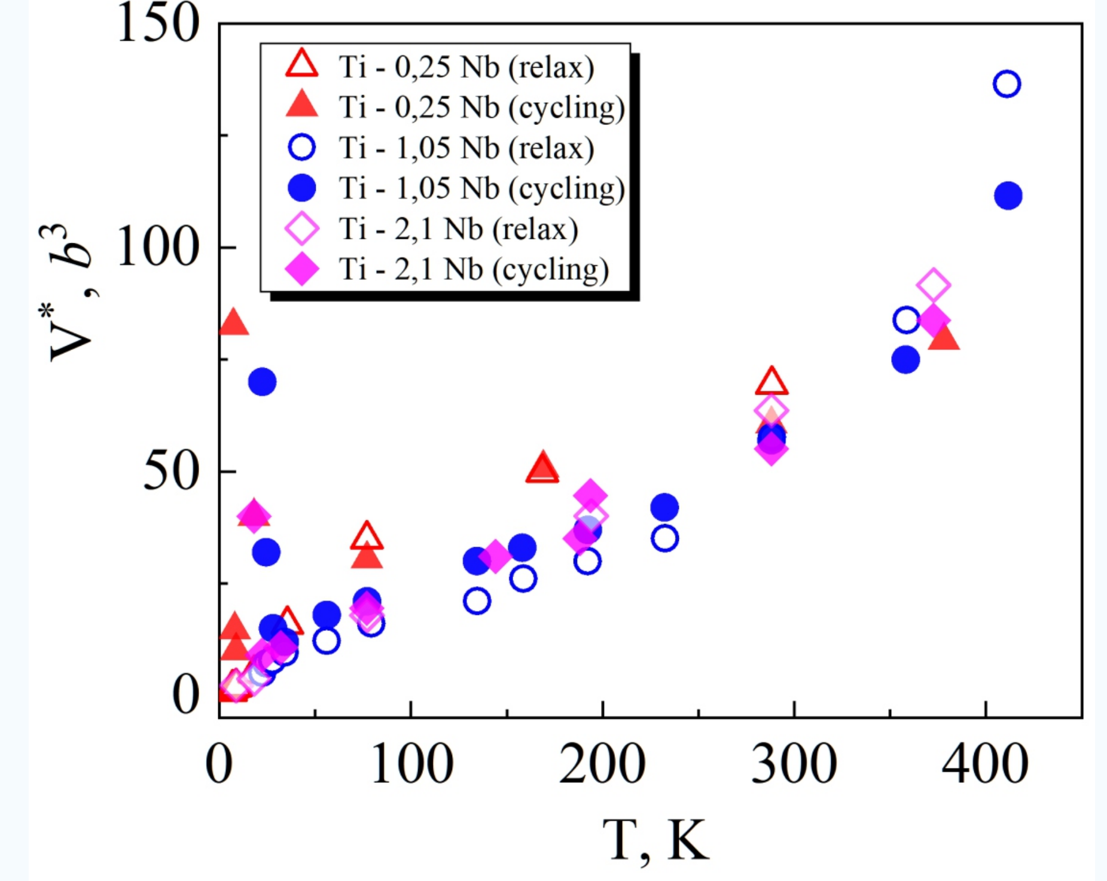

Fig. 4. Temperature dependences of the activation volume V^* *for Ti-Nb* ($b = 2{,}95\ 10^{-10}$ *m).*

The kinetics of thermally activated plastic deformation is usually described by the Arrhenius equation for the plastic strain rate $\acute{\varepsilon}$:

$$\acute{\varepsilon} = \acute{\varepsilon}_0 \exp\left[-H(\tau^*)/kT\right] \qquad (2)$$

where $\acute{\varepsilon}_0$ – the pre-exponential factor.

For identification of the plastic flow microscopic mechanisms crystals, much attention is paid to the measurements and analysis the activation volume V^* of the plastic deformation process:

$$V^* = -\left[\, dH(\tau^*)/d\tau^* \right] = kT\,(\triangle\ln\acute{\varepsilon}/\triangle\tau)_T \qquad (3)$$

The activation enthalpy $\mathbf{H(\tau^*) = 0.5Hc\,(1 - \tau^*/\tau_P)^{5/4}}$ (4)

$$\tau_0(T,\acute{\varepsilon}) = \tau_i + \tau_P\left[1 - (T/T_0)^{4/5}\right] \qquad (6)$$

$$(\triangle\tau/\triangle\ln\acute{\varepsilon})_T = (4\tau_P/5A)(T/T_0)^{4/5} \qquad (7)$$

$$A = \ln(\acute{\varepsilon}_0/\acute{\varepsilon}), \quad T_0 = Hc/2kA \qquad (8)$$

$$\tau_0(T) = \tau_i(T) + a_1 - a_2T^{4/5} \qquad (9)$$

$$(\triangle\tau/\triangle\ln\acute{\varepsilon})_T = a_3T^{4/5} \qquad (10)$$

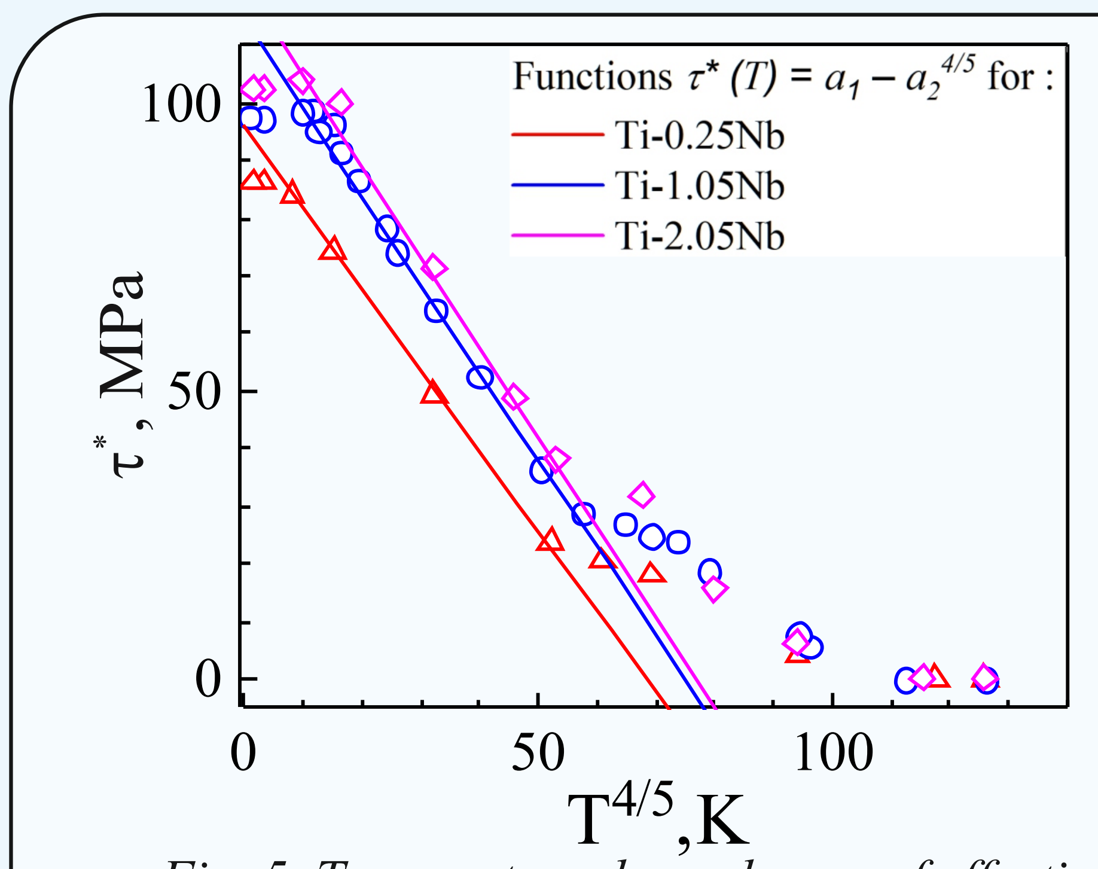

Fig. 5. Temperature dependences of effective stresses $\boldsymbol{\tau^*}$ *for α-Ti-Nb alloys in coordinates* $\boldsymbol{\tau^*} - \boldsymbol{T^{4/5}}$ *at the temperatures of 1.7 – 423 K.*

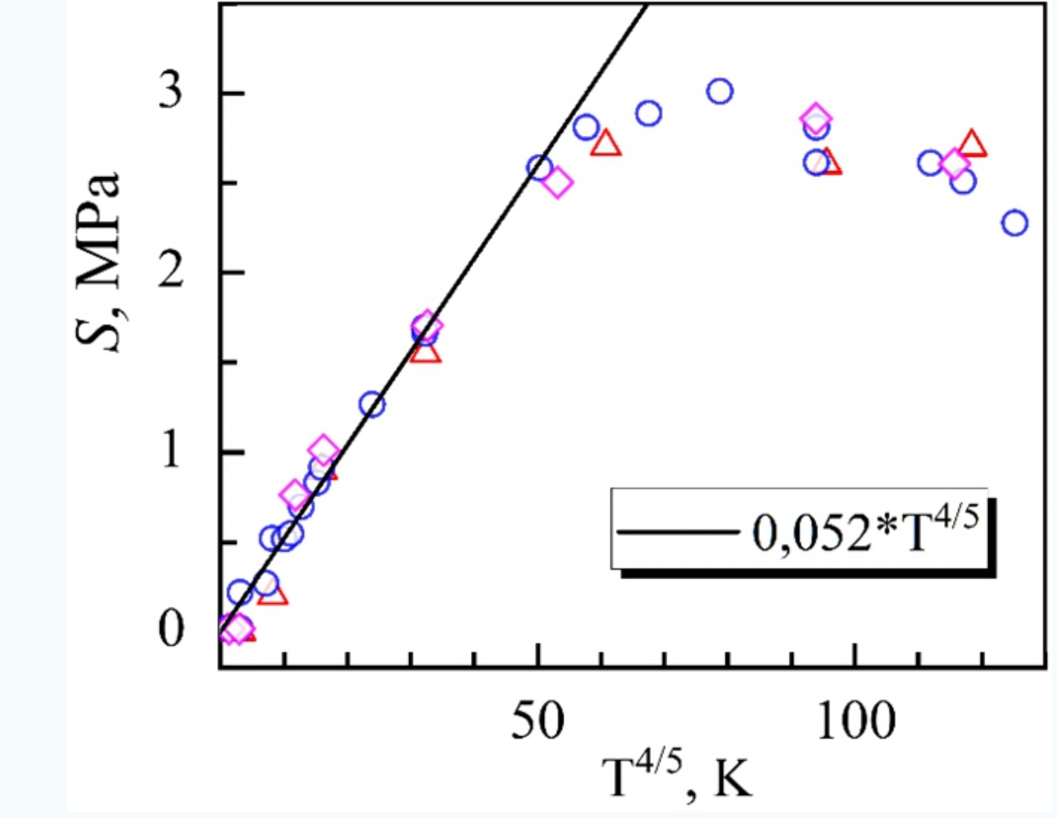

Fig. 6. Temperature dependence of the strain rate sensitivity $S = (\triangle\tau/\triangle\ln\acute{\varepsilon})_T$ *of α-Ti-Nb alloys. The solid curve shows the theoretical dependence of Eq. 7 for the parameters given in Table 2.*

Table 1. Values of approximation coefficients a1, a2, and a3 in relations (9) and (10).

Material	a_1, MPa	a_2, MPa·K$^{-4/5}$	a_3, MPa K$^{-4/5}$
α-Ti †	72	0.74	0.0325
Ti-0,25% Nb	95	1,3	0,051
Ti-1,05% Nb	117	1,61	0,052
Ti-2,1% Nb	124	1,67	0,052

Table 2. Empirical values of the parameters of the thermally activated theory

Parameters	Numerical values			
	α-Ti [1]	Ti-0,25Nb	Ti-1,05Nb	Ti-2,1Nb
b	$2{,}95\cdot10^{-10}$ m			
τ_P, MPa	73	95	121	128
T_0	308	209	210	226
A	18	20	25	25
ε_0, s^{-1}	$1.8\cdot10^4$	$2.1\cdot10^4$	$3.2\cdot10^7$	$3.2\cdot10^7$
H_c, J	$1.12\cdot10^{-19}$	$1.1\cdot10^{-19}$	$1.45\cdot10^{-19}$	$1.57\cdot10^{-19}$

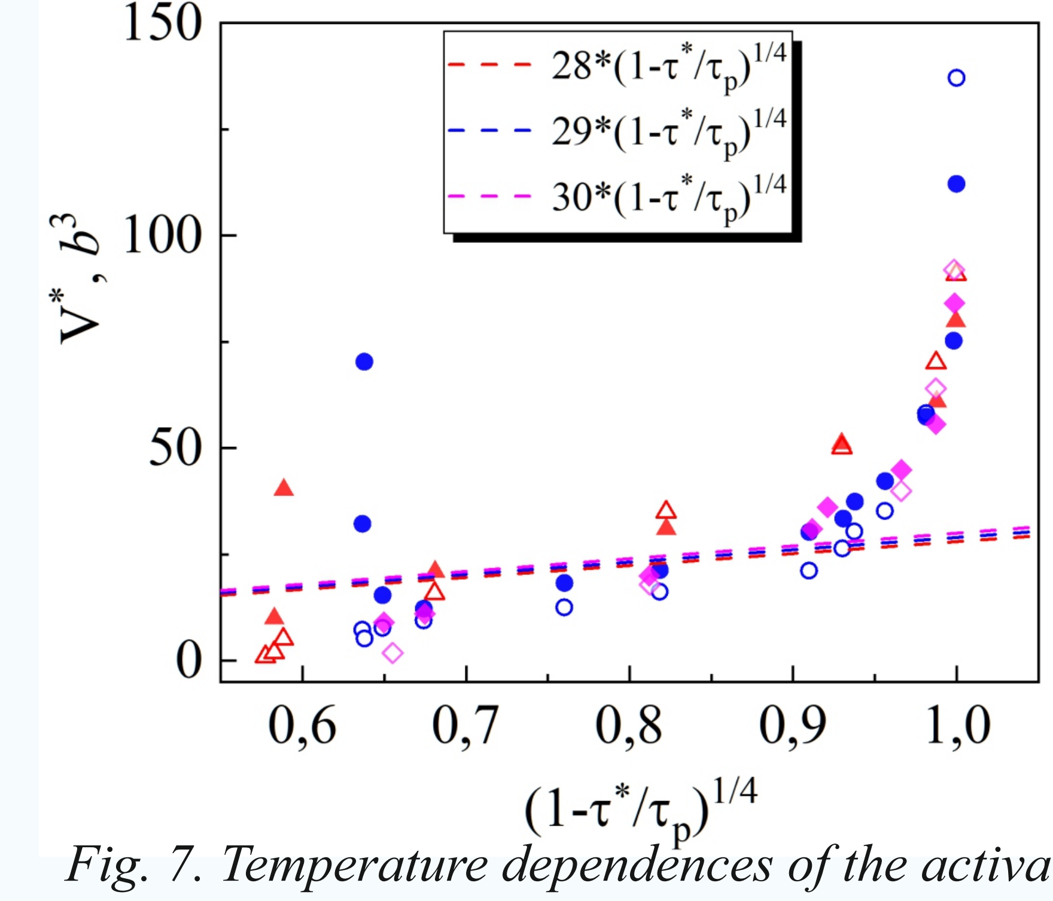

Fig. 7. Temperature dependences of the activation volume V^* *for Ti-Nb from the strain rate sensitivity β (Eq. 4) and the stress relaxation experiments*

Conclusions

- ✓ The plastic deformation patterns of hcp Ti-Nb solid solutions were studied to determine the influence of substitutional atoms on the mechanisms controlling the plasticity of high-purity titanium, where the role of interstitial impurity atoms is insignificant.
- ✓ The temperature dependences of the yield strength and its rate sensitivity were determined for Ti-Nb alloys (0.25–2.1 at.%) under quasi-static tension conditions over a wide temperature range (1.7–423 K).
- ✓ It was established that alloying with niobium, unlike dissolved interstitial elements (oxygen, nitrogen, etc.), does not affect the rate sensitivity and the activation volume of the plastic flow process, nor the type of their temperature dependence inherent in high-purity titanium.
- ✓ The experimental results are discussed within the framework of a theoretical model of thermally activated motion of a dislocation string in the Peierls relief. It was established that the studied temperature range can be divided into three, each with its own specific features of dislocation motion in the Peierls relief.
- ✓ It was shown that in the range of 18 K < T < 150 K, plastic flow of the studied α-alloys is controlled by thermally activated overcoming of Peierls barriers by dislocations of the $\{10\bar{1}0\}$ <11$\bar{2}$0> system via the mechanism of nucleation, expansion, and annihilation of paired kinks. Empirical estimates of the Peierls stress τ_P and the characteristic energy of the critical kink pair H_c were obtained.
- ✓ In the very low-temperature range (below 18 K), athermic yield strength and a lack of velocity sensitivity are observed, possibly due to the transition from thermally activated dislocation motion through Peierls barriers to dynamic (above-barrier) motion.

References
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