DEFORMATION BEHAVIOR OF HCP SOLID SOLUTIONS Ti-Nb UNDER TENSION IN THE TEMPERATURE RANGE 1.7 - 423 K

V.A Moskalenko, R.V. Smolianets

B.Verkin Institute for Low Temperature Physics and Engineering of NAS of Ukraine

smoljanets@ilt.kharkov.ua

Introduction

Plastic deformation of high-purity Ti at low temperatures occurs because the dislocations overcoming Peierls barriers according to the mechanism of nucleation, expansion, and annihilation of pair bends [1]. However, even at low concentrations of primarily interstitial atoms (oxygen and nitrogen) a significant increase of the yield stress is observed indicating their controlling role [2, 3]. To date, the mechanisms of alloys low-temperature plasticity based on alpha solid interstitial solutions have been studied (sufficient detail in the Ti–O system).[2, 3]. On the other hand, the systematic studies of the influence of substitution atoms on the deformation behavior of this group hcp metals have not. To fill this deficiency is aim of this work.

Experimental procedures

We studied titanium alloys with a concentration of **0.25, 1.05 and 2.1 at. % Nb** which alpha-substitutional solid solutions. The phase diagram of the Ti-Nb system is shown in Fig. 1. 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 size in the samples was $\boldsymbol{d}$ **= 35 µm** (measured metallography). Mechanical characteristics in the temperature range **1.7 – 420 K** were determined in experiments on quasi-static uniaxial tension with a strain rate of $\dot{\varepsilon} = 5 \times 10^{-4}\ s^{-1}$. In the case of uniaxial tension of polycrystalline samples, the maximum shear stress with respect to the tension axis $\boldsymbol{\tau_0 = 0{,}5\ \sigma_0}$ was taken τ_0.

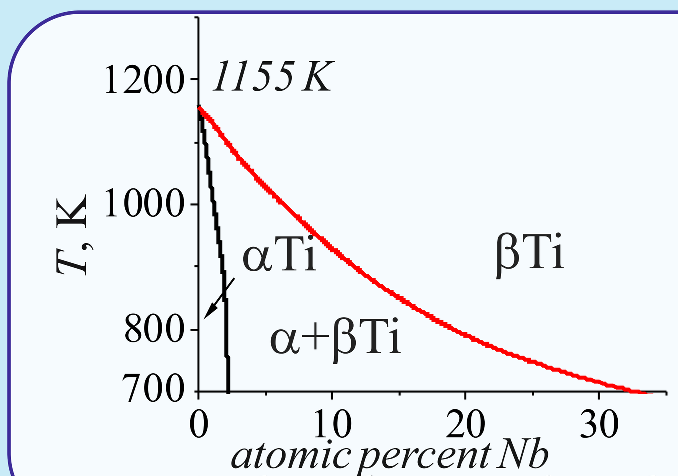

Fig. 1. Phase diagram of Ti–Nb.

Results and discussion

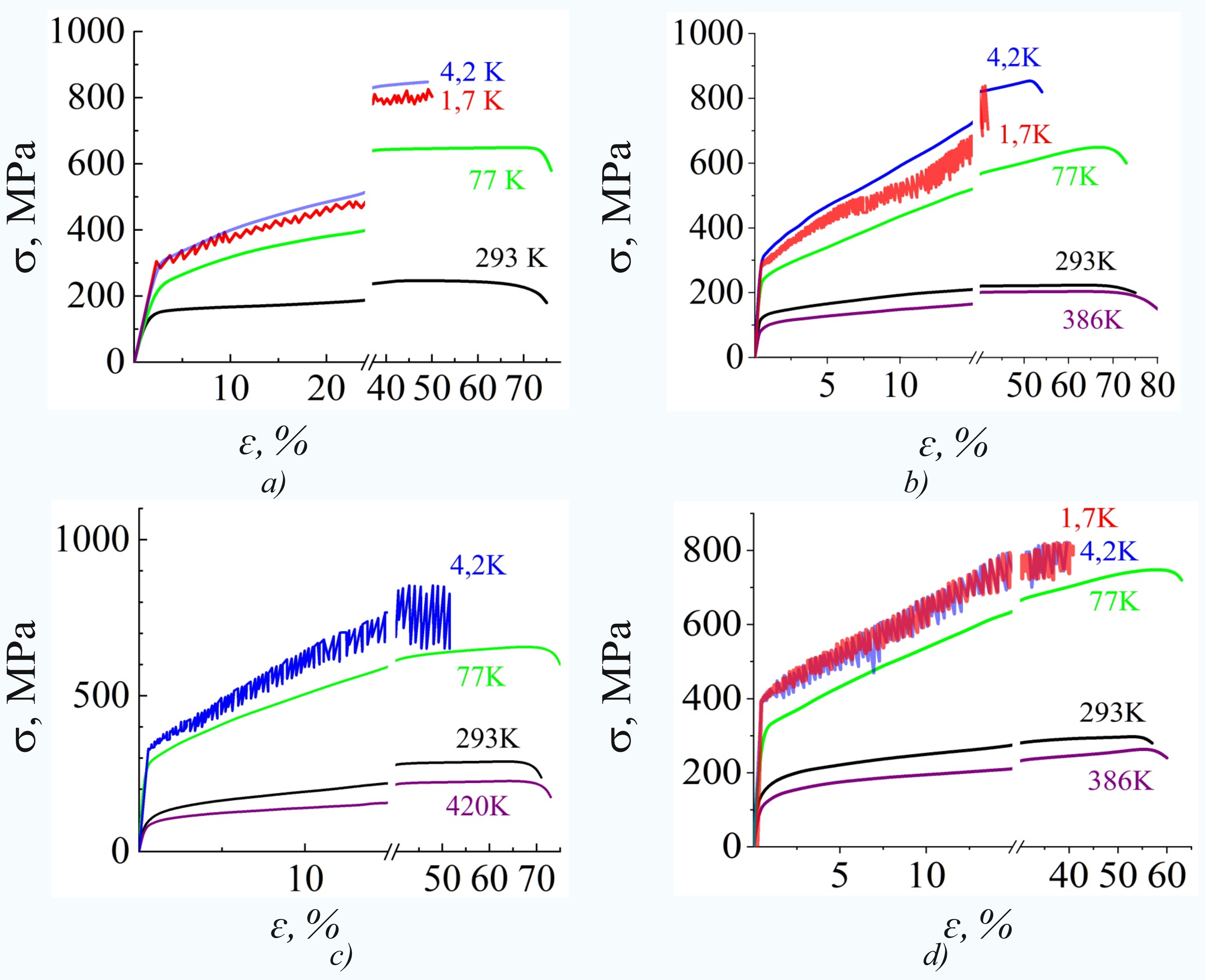

Fig. 2. Engineering tensile diagrams of solid solutions Ti-Nb in the temperature range 1,7-420 K: Ti(i) (a)[1] , Ti-0.25Nb (b), Ti-1.05Nb (c) and Ti-2.1Nb (d).

Table 1. The yield strength $\sigma_{0,2}$, ultimate strength σ_u and relative elongation δ of Ti-Nb alpha alloys.

Alloy, at. %Nb	293⁰ K			77⁰ K			20⁰ K			4,2⁰ K		
	$\sigma_{0.2}$, MPa	σ_u, MPa	δ, %	$\sigma_{0.2}$, MPa	σ_u, MPa	δ, %	$\sigma_{0.2}$, MPa	σ_u, MPa	δ, %	$\sigma_{0,2}$, MPa	σ_u, MPa	δ, %
Ti(i)	110	250	71	176	650	74	270	830	67	280	848	49
Ti-0,25 Nb	113	225	71	178	660	75	275	920	63	284	852	52
Ti-1,05 Nb	137	235	69	245	666	73	350	940	62	352	915	48
Ti-2,1 Nb	195	285	55	380	755	61	490	1020	51	510	960	40

In Fig. 2 shows typical stress-strain curves under quasi-static tensile deformation for unalloyed high purity Ti and Ti-Nb alloy over a wide temperature range (1.7 - 420 K). The stress-strain curves, which are smooth at room and moderately low temperatures below the threshold temperature ***Ta***, become sawtooth-shaped, reflecting the intermittent or jump-like plastic flow nature of the plastic flow. This feature is associated with the transition of the process from a thermally activated mode to a quasi-dynamic one, which is caused by an increase in the value of the inertial properties of dislocations when they move through a network of local obstacles, where the condition for the manifestation of inertia is the fulfilment of the inequality:

$$BL << 2\pi\,(AE_L)^{1/2} \qquad (1),$$

here $\boldsymbol{B}$ is the coefficient of dynamic friction, $\boldsymbol{L}$ is the length of the dislocation segment, $\boldsymbol{E_L = Gb^2/2}$ is the intrinsic energy per unit length of the dislocation, $\boldsymbol{A} = \rho\boldsymbol{b}^2/\pi$ is the effective mass per unit length of the dislocation, ρ is the density of the material, $\boldsymbol{G}$ is the shear modulus and $\boldsymbol{b}$ is Burger's vector. The close concentration of interstitial impurity atoms C(O+N) in Ti and Ti-Nb alloys allows us to consider the dislocation segment length $\boldsymbol{L} = \beta\boldsymbol{b}\boldsymbol{C}^{-1/2}$ to be preserved in them [3].

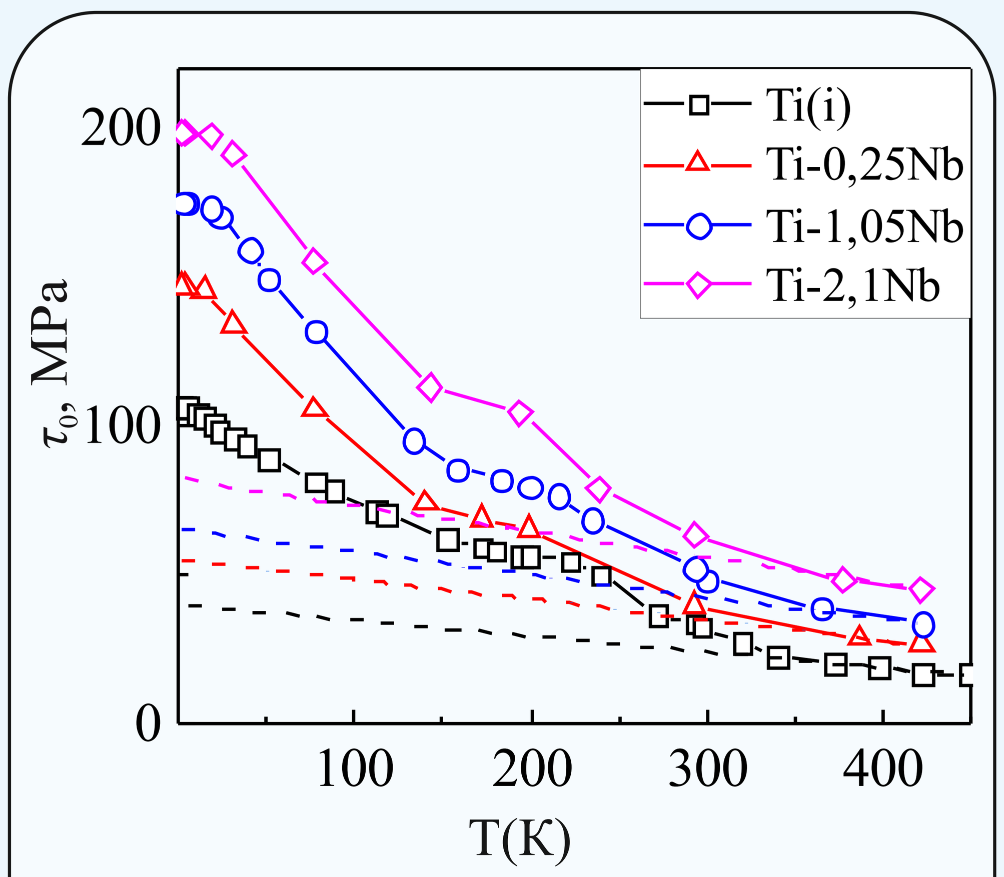

Fig. 3. Temperature dependences of yield strength $\tau_0 = 0{,}5\ \sigma_0$ of solid solutions Ti-Nb . Dashed lines – temperature dependences of internal stresses according to the formula (7).

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

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

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

The enthalpy of activation H(τ*) for dislocations move through Peierls barriers:

$$H(\tau^*) = 0{,}5H_0\,[1 - (\tau^*/\tau_c)]^{5/4} \qquad (3)$$

$$\tau_0(T) = \tau_i + \tau_c\,[1 - (T/T_0)^{4/5}] \qquad (4)$$

The correspondence of the experimental data to formula (4) can be checked if

$$\tau_0(T) = \tau_{i0} + a_1 + a_2\,T^{4/5} \qquad (6)$$

$$\tau_{i0} = \tau_0(423\ K)\,[C_{66}(T)/C_{66}(423K)] \qquad (7)$$

Table 2. The coefficients $\boldsymbol{a_1}$, $\boldsymbol{a_2}$ and the energy parameter ***0,5Hc***

	a₁	a₂	0,5***Hc***, eV
Ti-0,25Nb	105	1,3	0,35
Ti-1,05Nb	128	1,75	0,42
Ti-2,1Nb	140	1,82	0,5

The enthalpy of activation ***0,5Hc*** in solid solutions Ti-Nb according with the energy value of a single kink $\boldsymbol{U_k}$ **= 0,35 eV** [4].

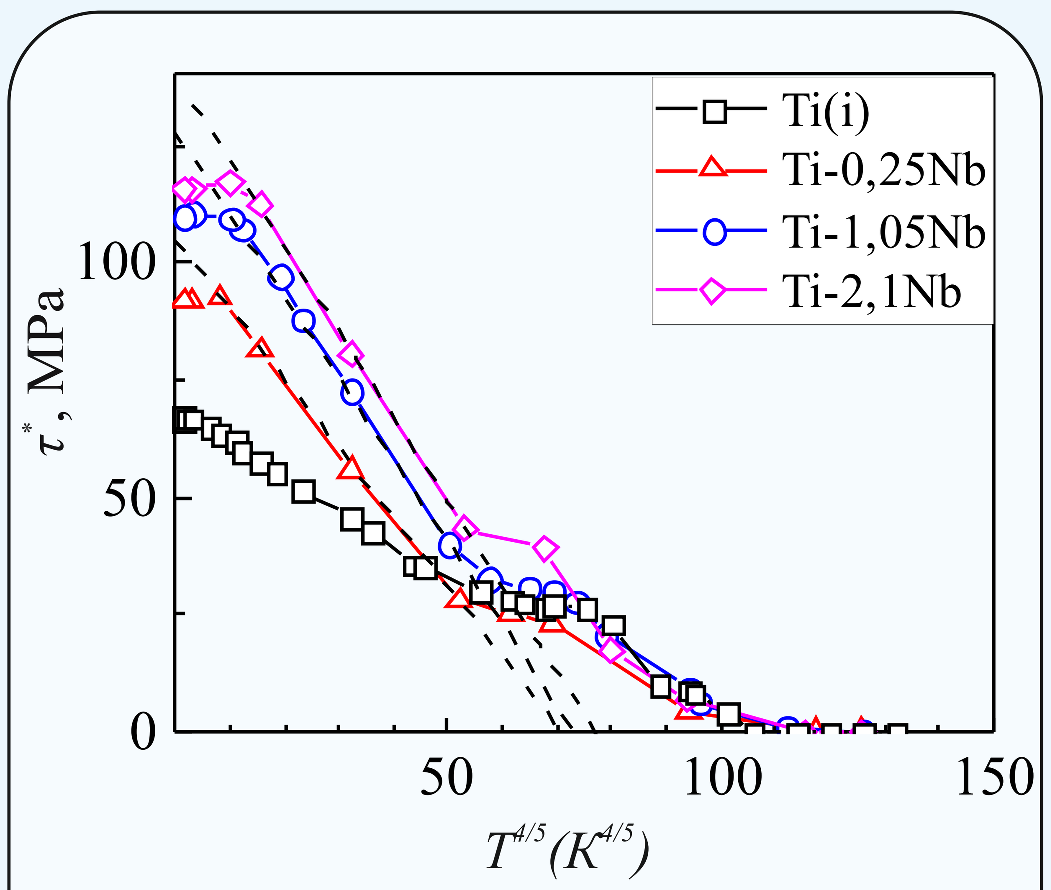

Fig. 4. Temperature dependences of the effective stress $\tau^* = \tau_0 - \tau_{i0}$ for solid solutions Ti-Nb in coordinate $T^{4/5}$ corresponding to Eq(6). Dashed lines – function of the effective stresses τ^* according to the formula (4).

Conclusions

- ✓ An experimental study was carried out on the deformation behavior of alpha solid substitution solutions of Ti-Nb alloys with concentrations of 0.25, 1.05 and 2.1 at. % Nb with low content of interstitial impurities (C(O+N)) < 0.1 at. %) in the temperature range 1.7 – 423 K.
- ✓ It is shown that the stress-strain curves, which are smooth at room and moderately low temperatures below the threshold temperature *Ta*, become sawtooth-shaped, reflecting the abrupt nature of the plastic flow. It is assumed that the weaker (than interstitial impurity atoms) effect of niobium doping on the threshold temperature *Ta*, this low-temperature feature, which is associated with the manifestation of inertial properties of dislocations, is determined by a change in the dynamic friction coefficient B.
- ✓ The mechanical properties of Ti-Nb binary alpha alloys were determined in the temperature range 1.7 – 423 K, which indicate weak solid solution strengthening of Ti when alloyed with niobium and the preservation of its high ductility at low temperatures, which is explained by a combination of sliding and active twinning.
- ✓ Thermal activation analysis of experimental data on the temperature dependence of the yield stress was carried out within the framework of a theoretical model of the dislocation string activated movement in the Peierls relief. It is shown that plastic flow in alpha solid solutions of Ti-Nb in the region of moderately low temperatures (18 < T < 150 K) occurs as a result of thermally activated overcoming of Peierls barriers through the mechanism of nucleation, expansion and annihilation of paired kinks.

References

1. *V. A. Moskalenko, V. D. Natsik, V. N. Kovaleva, Low Temp. Phys. 31, 907 (2005)*
2. *H. Conrad, Prog. Mater. Sci. 26, 123 (1981)*
3. *V.N. Kovaleva, V.A. Moskalenko and V.D. Natsik, Phil. Mag. 70, 423 (1994)*
4. *V.A. Moskalenko, V.N. Kovaleva, V.D. Natsik et all. Low Temp. Phys 1996;22:1108.*
5. *E. S. Fisher and C. J. Renken, Phys Rev. 135, A482 (1964).*