Strain rate dependent deformation behavior of Ti-Nb alpha-alloys system at low temperatures

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When identifying microscopic mechanisms of crystals dislocation plasticity, much attention is paid to measuring and analyzing such thermally activated parameters as the temperature dependences of the critical shear stress and its strain rate sensitivity. The physical mechanism of low-temperature plasticity by slip of high-purity titanium consists of Peierls barriers overcoming by dislocations as a process of nucleation, expansion and annihilation of paired kinks [1]. The influence of interstitial impurities, which provide the most pronounced changes in the mechanical properties of Ti, has been studied in detail [2,3]. When the concentration of interstitial impurities (generally O and N) is higher than 0.1 at.%, the controlling mechanism becomes the overcoming of local impurity barriers by dislocations. The investigation influence of substitution atoms on the deformation behavior and low-temperature plasticity mechanisms in Ti and other HCP metals are very limited. It is precisely the alloying with chemical elements of this type that plays an important role in determining the chemical and physical-mechanical properties of modern Ti alloys.

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 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.

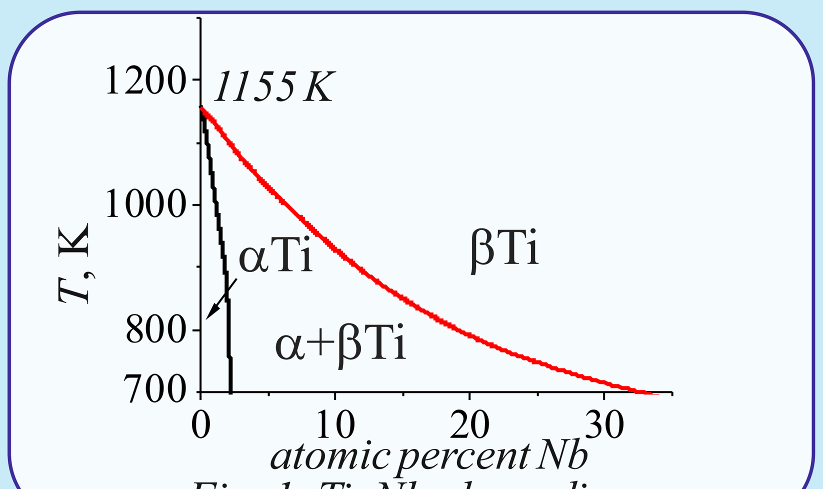

Fig. 1. Ti–Nb phase diagram

Results and discussion

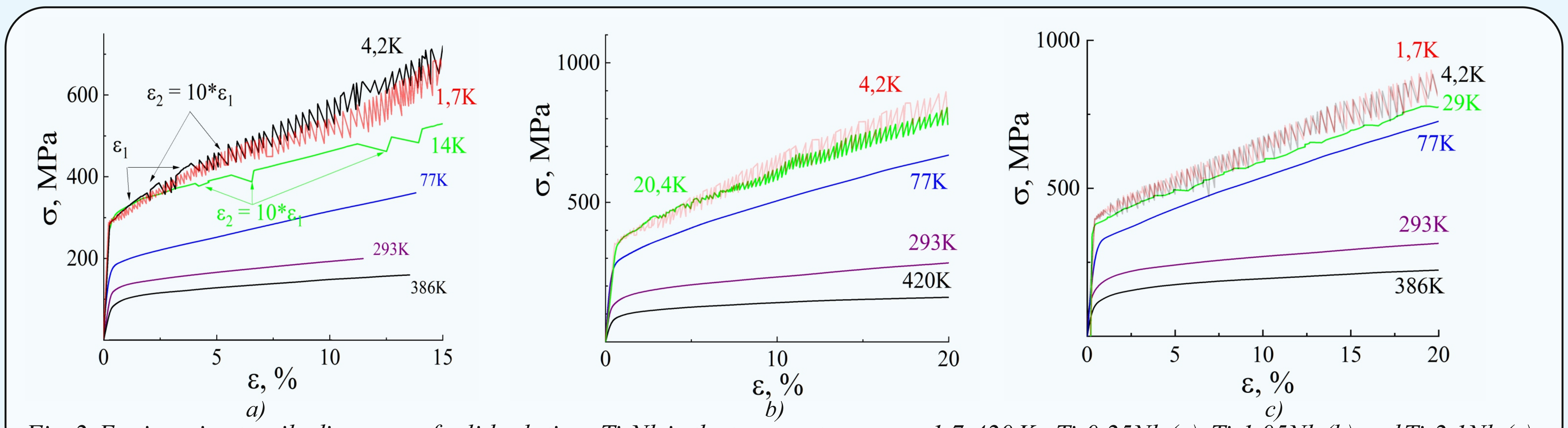

Fig. 2. Engineering tensile diagrams of solid solutions Ti-Nb in the temperature range 1,7-420 K: Ti-0.25Nb (a), Ti-1.05Nb (b) and Ti-2.1Nb (c)

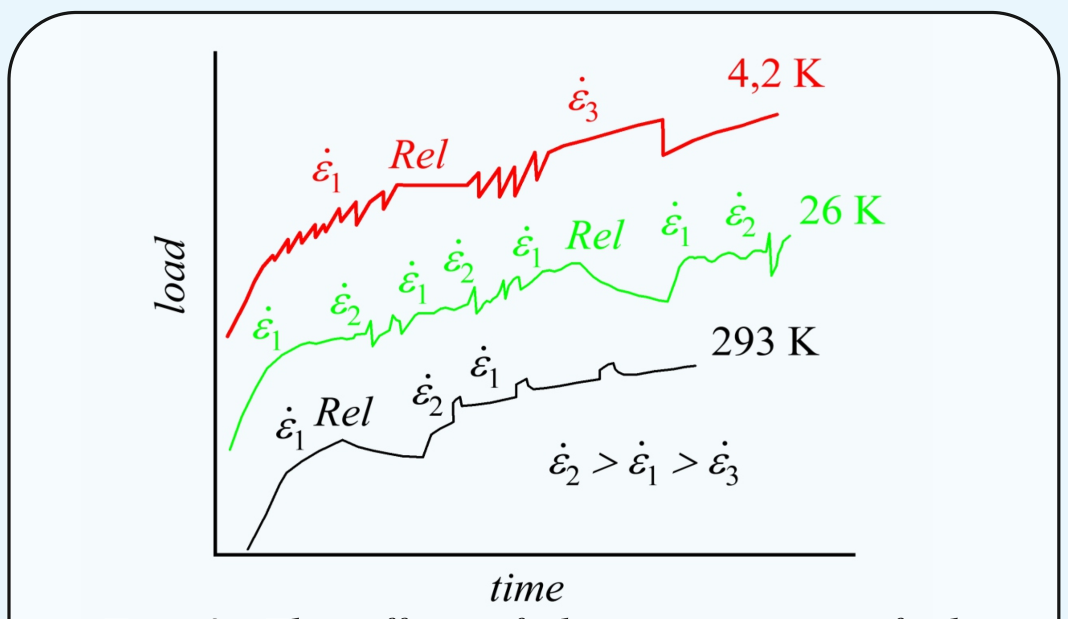

Fig. 3. The effect of the strain rate of plastic deformation on the nature of plastic flow in the alpha alloy Ti – 2.1 at.% Nb at the temperature range of 1.7 – 423 K.

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 - 386 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: $BL << 2\pi\,(AE_L)^{1/2}$ (1), here B is the coefficient of dynamic friction, L is the length of the dislocation segment, $E_L = Gb^2/2$ is the intrinsic energy per unit length of the dislocation, $A = \rho b^2/\pi$ is the effective mass per unit length of the dislocation, ρ is the density of the material, G is the shear modulus and 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 $L = \beta b C^{-1/2}$ to be preserved in them [3].

In Fig. 4 shows the effect of niobium alloying on the strain rate sensitivity of the deforming $\beta = (\triangle\tau/\triangle ln\acute{\varepsilon})_T$ (the important differential characteristic at identifying the plasticity dislocation mechanism). The β(T) at T >25 K are typical for thermally activated plastic deformation for most metals. In the region at lower temperatures, the value of is slump to near zero at T=2 – 4 K (depend on the concentration of Nb), indicating on the athermal nature of the process.

The absolute values of β are practically independent on the concentration of Nb.

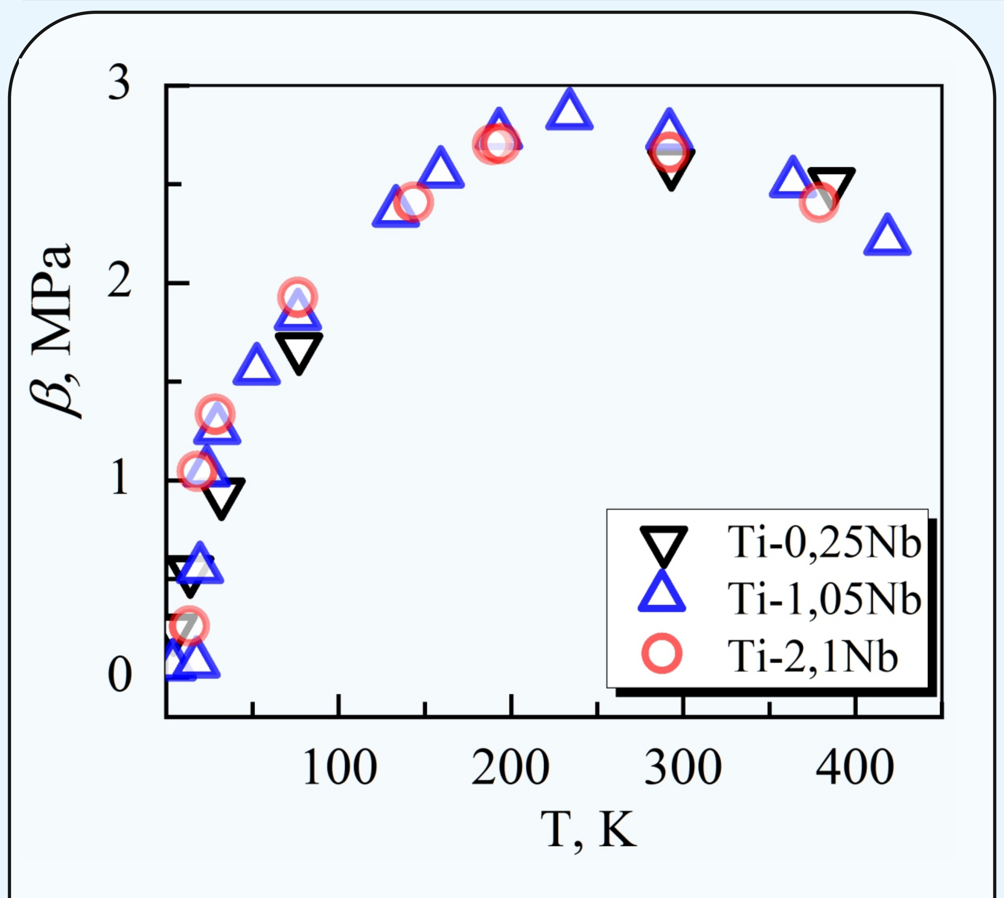

Fig. 4. Temperature dependences of strain rate sensitivity $\beta = (\triangle\tau/\triangle ln\acute{\varepsilon})_T$ of Ti-Nb.

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

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

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:

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

In Fig. 5 shows the temperature dependences of the activation volume V^* obtained from the strain rate sensitivity β (Fig. 4) using of the formula

$$V^* = kT/\beta \quad (4)$$

and the stress relaxation experiments.

The found of V^* are close to the obtained values for titanium with concentration O_2 < 0.1 at.% [1,4], where the controlling mechanism is the overcoming of Peierls barriers by dislocations.

The absence of Nb effect content on the value V^* and temperature dependence of the strain rate sensitivity β (Fig. 5) may be indicate about the conservation of the alloys plasticity mechanism wich inherent for high-purity titanium.

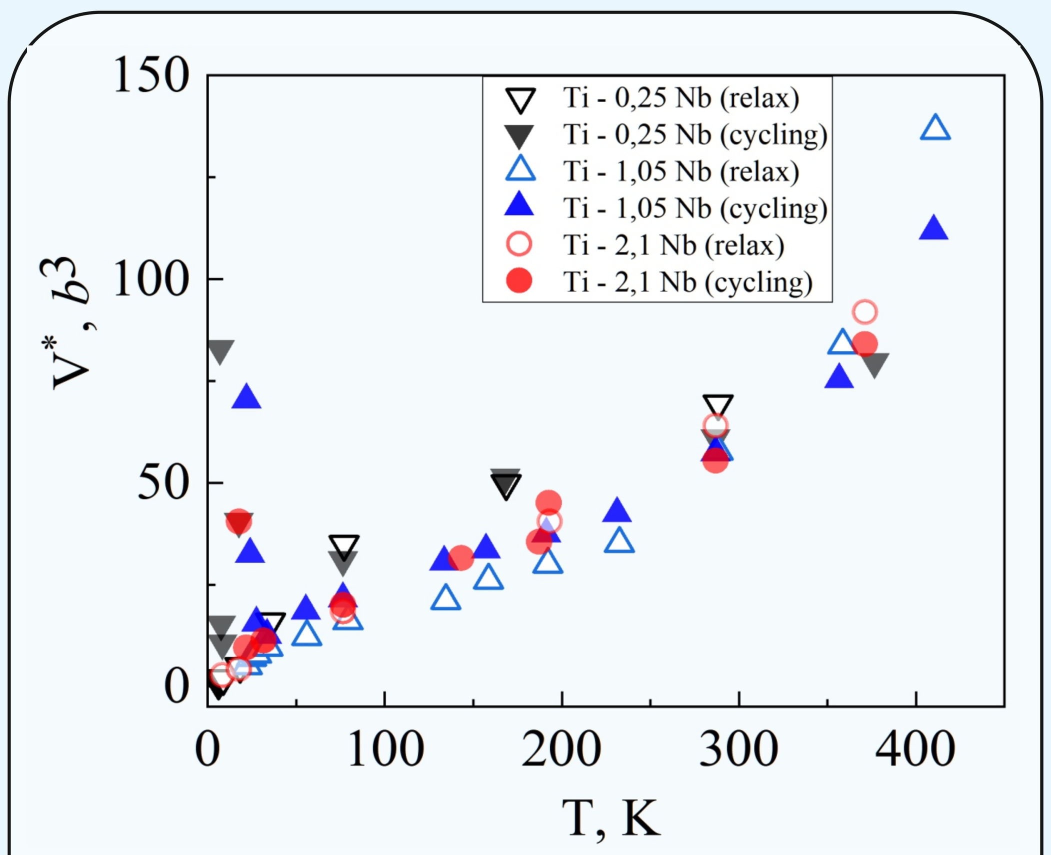

Fig. 5. Temperature dependences of the activation volume V^* for Ti-Nb from the strain rate sensitivity β (Eq. 4) and the stress relaxation experiments ($b = 2{,}95\ 10^{-10}$ m).

Conclusions

When studying of the low-temperature plastic deformation mechanisms in hcp Ti-Nb system alloys at the temperature range of 1.7 - 423 K it was shown:

- ✓ High-purity Ti alloying by Nb in limited of the alpha-solid solution (0.25–2.1 at.%) causes an increase of the threshold temperature Ta transition from the thermally activated to the low-temperature plasticity quasi-dynamic mechanisms (the appearance of the dislocation inertial properties) can be explained by a change of the dynamic friction coefficient B at their movement through a network of local barriers.
- ✓ Alloying high-purity titanium with niobium (a substitution element) at a concentration corresponding to the alpha solid solution does not affect on the rate sensitivity of the deforming stress $\beta = (\triangle\tau/\triangle ln\acute{\varepsilon})_T$.
- ✓ The observed absence of the Nb content effect on the value and temperature dependence of the activation volume of the plastic deformation process may indicate about the preservation of the Ti-Nb substitution in alpha-solid solutions by the controlling mechanism of overcoming the Peierls barriers by dislocations, which is inherent in high-purity titanium.

References

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