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Evolution of Young's modulus and microplastic characteristics in VT1-0 titanium with different microstructures under cyclic loading

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The evolution of the Young's modulus and microplastic properties of VT1-0 titanium in the submicrocrystalline (SMC) and microcrystalline (MC) states was studied at various stages of fatigue testing. Using the acoustic method of a composite piezoelectric vibrator, the amplitude dependences of the elastic modulus $E(\varepsilon)$ and the vibration decrement $\delta(\varepsilon)$ were studied, and microplastic deformation diagrams were constructed. It was established that cyclic loading affects the properties of the MC and SMC states differently. The results of this study are important for understanding the mechanisms of fatigue failure of ultrafine-grained titanium alloys and predicting their durability.

Keywords: VT1-0 titanium, Young's modulus, fatigue testing, sub- and microcrystalline structure, microplastic deformation.

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Owing to their unique combination of high specific strength, corrosion resistance, and biocompatibility, titanium alloys (specifically, technical titanium VT1-0) are used widely in the aerospace, medical, and chemical industries [1,2]. In the course of operation, structures are often subjected to alternating cyclic loads. This leads to fatigue failure, which is one of the main reasons for failure of individual elements [3].

One of the most effective ways to improve the mechanical properties of metals and alloys is to control their structure at the micro- and nanolevel. Severe plastic deformation methods provide an opportunity to obtain bulk submicrocrystalline and ultrafine-grained materials with a grain size below $1\,\mu$m. Compared to its coarse-crystalline counterparts, this structure provides a significant increase in yield strength and static and cyclic strength [4,5]. However, the response of such materials to cyclic loading has been studied to a much lesser extent [6,7]. Fatigue behavior cannot be predicted directly from static strength characteristics, since it is shaped by a complex interaction of such processes as damage accumulation, dislocation generation and annihilation, internal stress relaxation, and fracture nucleation.

The evolution of both macromechanical characteristics (fatigue limit, number of cycles to failure) and fundamental physical and mechanical properties at various stages of fatigue loading is of particular importance. These properties include the elastic modulus and microplastic deformation parameters. Young's modulus is an important characteristic that defines the rigidity of a material and its resistance to elastic deformation. Its variation under cyclic loading may serve as an indicator of damage accumulation, relaxation of internal stresses, or phase transformations. Microplastic properties manifested at small deformation amplitudes on the order of 10^{-5} are a highly sensitive indicator of the state of the crystal lattice, the density of defects (dislocations, vacancies), and the interaction between them. The analysis of microplastic deformation diagrams allows one to determine the micro-yield stress, which is an important parameter characterizing the material's resistance to initial plastic deformation.

The present study is focused on the experimental examination of evolution of Young's modulus and microplastic characteristics of titanium VT1-0 in submicrocrystalline (SMC) and microcrystalline (MC) states at various stages of cyclic fatigue testing and is aimed at establishing the patterns and physical mechanisms of damage accumulation as functions of the initial structural state.

Samples of titanium alloy VT1-0 in SMC and recrystallized MC states were examined. The MC structure was formed by annealing titanium with the SMC structure for 1 h at a temperature of 823 K. The average grain size was 0.2 and $2-3\,\mu$m for SMC and MC states, respectively. The results of structural studies for MC and SMC states before testing and the cyclic fatigue testing regimes were detailed in [8]. Structural data for fatigue-tested samples were reported in [9].

The microplastic properties of the alloy under study in MC and SMC states were examined before and after fatigue tests with $4 \cdot 10^5$, $6 \cdot 10^5$, and $8 \cdot 10^5$ cycles. The characteristics of microplastic properties after $2 \cdot 10^5$ and $1 \cdot 10^6$ test cycles were determined additionally for the experimental samples with the SMC structure. The samples for fatigue testing had the form of an I-beam blade with a working area thickness of 1 mm. Following fatigue testing, samples in the form of a rectangular rod with a cross section of 1×3 mm and an approximate length of 20 mm were fabricated for acoustic experiments from the working section of such blades.

Elastic and microplastic properties were determined using the acoustic method of a composite piezoelectric vibrator. The procedure was detailed in [10]. Tests were carried out at a frequency of approximately 100 kHz within a wide range of vibrational deformation amplitudes ε.

Figures 1, *a*, *b* show the amplitude dependences of Young's modulus $E(\varepsilon)$ and decrement $\delta(\varepsilon)$ for MC and SMC samples of titanium VT1-0 measured under increasing and decreasing amplitude.

It can be seen from Figs. 1, *a*, *b* that the elastic modulus prior to testing in the SMC state is higher than the one in the MC state (109.1 and 104.6 GPa, respectively). Subjected to cyclic loading, SMC and MC titanium samples behave in significantly different manners. Figure 1, *a* makes it evident that Young's modulus of MC samples after $N = 4 \cdot 10^5$ loading cycles increases from 104.6 to 107.1 GPa. As the number of cycles increases to $6 \cdot 10^5$ and $8 \cdot 10^5$, the elastic modulus decreases consistently to 103.5 and 100.9 GPa, respectively. Similar to the elastic modulus, decrement δ first increases by a factor of almost 2 (from $25 \cdot 10^{-5}$ to $46 \cdot 10^{-5}$) under cyclic deformation, but decreases consistently as the number of test cycles grows (to $33 \cdot 10^{-5}$ and $20 \cdot 10^{-5}$).

In the case of SMC titanium (Fig. 1, *b*), the elastic modulus decreases noticeably (relative to the state before testing) at $N = 2 \cdot 10^5$ (down to 102.5 GPa). An increase in the number of test cycles does not exert any significant influence on Young's modulus of SMC titanium, which remains within the range of 102–104 GPa for all the samples examined after cyclic loading. The decrement for SMC titanium varies less significantly than the same parameter for MC samples. Specifically, tests at $N = 2 \cdot 10^5$ have virtually no effect on δ. An increase in the number of cycles leads to a slight reduction of the decrement (the minimum value is $120 \cdot 10^{-5}$, which is 30 % lower than the value determined before the test).

Figures 2, *a*, *b* show the diagrams of microplastic deformation $\sigma(\varepsilon_d)$ plotted on the basis of the $E(\varepsilon)$ dependences measured at the first increase in amplitude. Amplitudes of vibrational stresses $\sigma = E\varepsilon$ are plotted on the ordinate axis, and nonlinear inelastic deformation $\varepsilon_d = \varepsilon(\Delta E/E)_h$, where $(\Delta E/E)_h = (E - E_i)/E_i$ is the amplitude-dependent modulus defect (E_i is the modulus measured at small amplitudes where it remains independent of ε), is plotted on the abscissa axis.

What is common to both types of samples is that curve *1*, which corresponds to the state before testing, is positioned mostly above the other curves. The subsequent curves measured under cyclic loading are positioned below (curves *2* and *3* for MC and SMC states). With a large number of cycles ($N = 8 \cdot 10^5$ for the MC state and $N = 6 \cdot 10^5$for the SMC state), microplastic flow stress σ

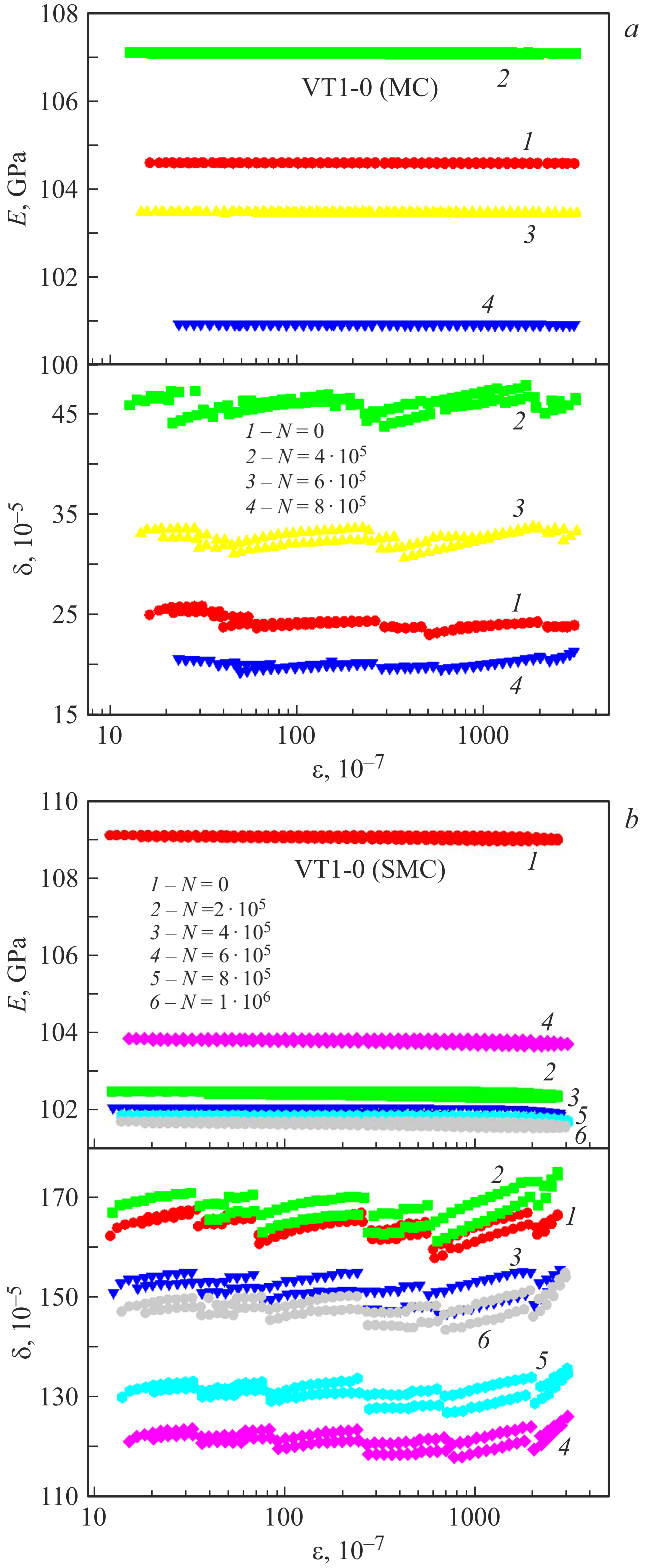

Figure 1. Amplitude dependences of Young's modulus (E) and vibration decrement (δ) of titanium VT1-0 before and after fatigue tests with different numbers of loading cycles (N). *a* — MC structure; *b* — SMC structure. Measurements were performed at room temperature.

tends to increase slightly (curve *4* in Fig. 2, *a* for the MC state; curves *4–6* in Fig. 2, *b* for the SMC state) and approaches curve *1*.

Let us analyze the obtained data. To do this, we consider the experimental data presented in Fig. 3 in the form of dependences of E, δ_i, and σ_s on the number of loading cycles; the results of density measurements for all the studied samples are given in the table.

The key difference in the behavior of Young's modulus between MC and SMC titanium is that E decreases after testing of MC samples at $N = 4 \cdot 10^5$ and increases after similar tests of SMC samples. As the number of test cycles increases, E decreases noticeably in the MC state, while Young's modulus for the SMC state varies around 102 GPa ($E = 104$ GPa only at $N = 6 \cdot 10^5$). According to the table data, the density of both types of titanium samples decreases during fatigue testing. Therefore, the elastic modulus reduction for SMC titanium appears to be natural (the modulus value is proportional to density). The non-monotonic behavior of Young's modulus E for MC titanium may be attributed to the following. High local stresses emerge in MC samples in the process of plastic deformation (cyclic fatigue testing), which leads to an increase in Young's modulus [11]. At the same time, discontinuities (nano- and micropores, microcracks) forming during long-term fatigue tests reduce the modulus value. The process of accumulation of microdiscontinuities prevails over the influence of internal stresses, which is observed as a reduction in Young's modulus.

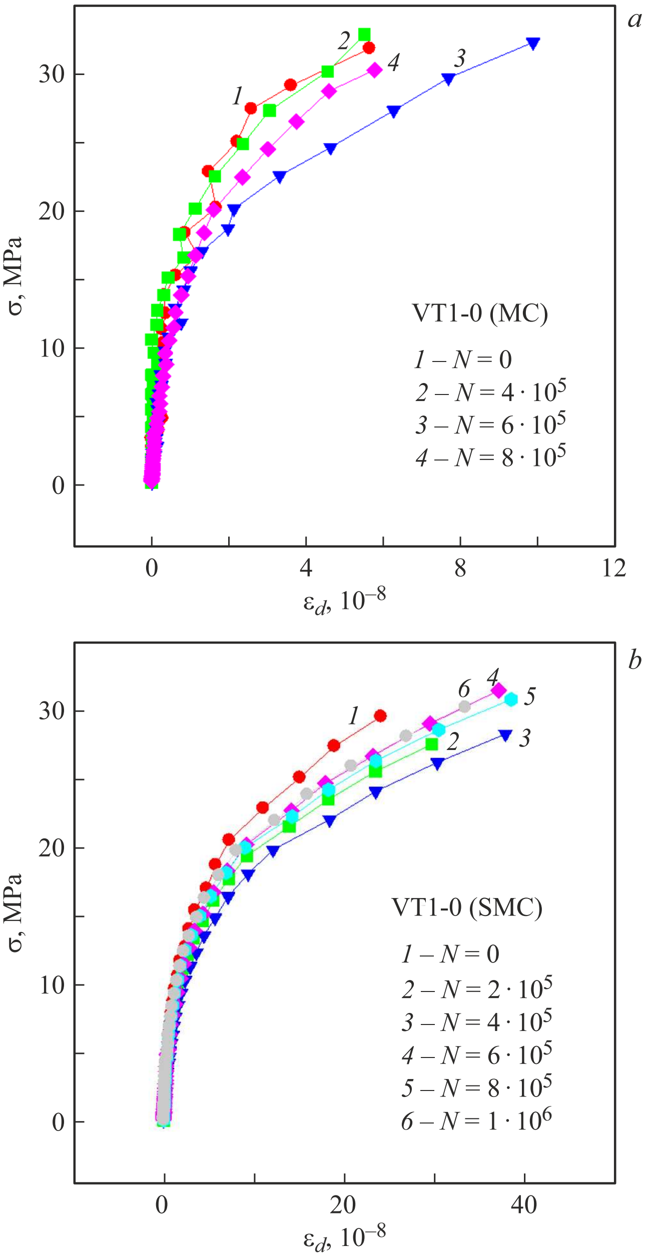

Figure 2. Microplastic deformation diagrams for titanium VT1-0 before and after fatigue tests with different numbers of loading cycles (N). *a* — MC structure; *b* — SMC structure. Measurements were performed at room temperature.

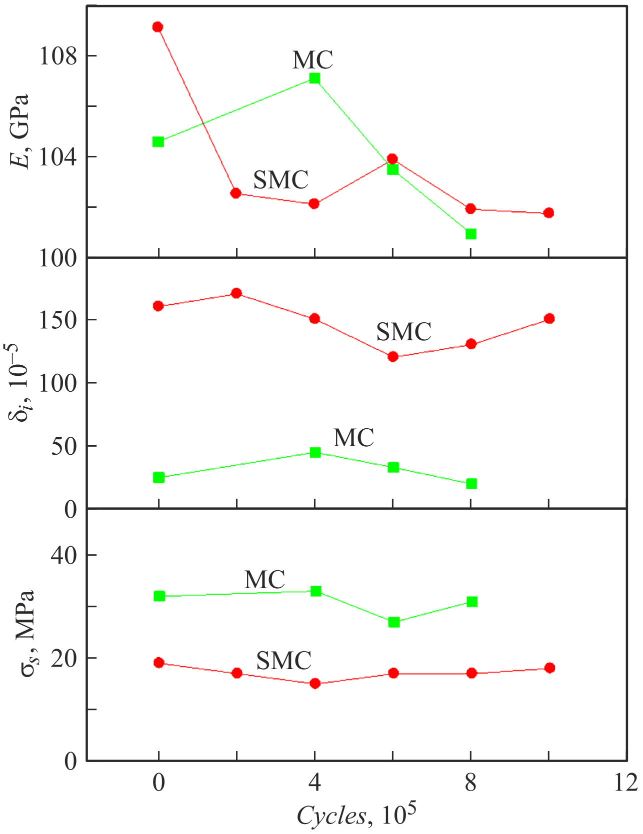

Figure 3. Dependences of Young's modulus E, amplitude-independent decrement δ_i, and micro-yield stress σ_s on the number of fatigue testing cycles for titanium VT1-0 in MC and SMC states. The parameters were determined under inelastic deformation $\varepsilon_d = 6.0 \cdot 10^{-8}$. Measurements were performed at room temperature.

SMC samples, which were prepared under intense plastic deformations, have significantly higher levels of internal stresses (before cyclic fatigue testing) than MC samples. It was demonstrated in numerous studies that intense plastic

Density ρ and density defect $\Delta\rho/\rho$ (loosening) of SMC and MC titanium samples for different numbers of loading cycles N

Parameter	N					
	0	$2 \cdot 10^5$	$4 \cdot 10^5$	$6 \cdot 10^5$	$8 \cdot 10^5$	10^6
ρ, g/cm^3 (MC)	4.4987	–	4.4981	4.4964	4.4866	–
$\Delta\rho/\rho$, % (MC)	0	–	0.01	0.05	0.27	–
ρ, g/cm^3 (SMC)	4.4963	4.4948	4.4846	4.4812	4.4749	4.4709
$\Delta\rho/\rho$, % (SMC)	0	0.03	0.26	0.34	0.48	0.57

deformation leads to the emergence of high internal stresses, which affect a number of physical and mechanical properties of metallic materials. Analyzing the data in the table, one may note that the density reduction ($\Delta\rho/\rho$) during fatigue testing is significantly more pronounced in SMC titanium than in MC samples. Therefore, the density factor here is likely to play a more important role than the influence of internal stresses. Note that the density of SMC samples before cyclic testing is lower than the density of MC samples (see the $N = 0$ column in the table). As was demonstrated in [8], this difference is attributable to the presence of nanopores with a size on the order of 20 nm, which form when the SMC structure is prepared. A higher initial concentration of microdiscontinuities in SMC titanium may contribute to a more intense additional accumulation of microdiscontinuities, which act as nuclei for pore growth.

The dependence of logarithmic decrement for SMC samples is positioned significantly higher than the one for MC titanium (Fig. 3), which is likely attributable to a higher density of grain boundaries, where ultrasound energy is dissipated, in the SMC state. In MC samples, the nature of the logarithmic decrement dependence is close to that observed for the elastic modulus: a peak at $N = 4 \cdot 10^5$ is followed by reduction at larger numbers of cycles.

The dependence for SMC samples is opposite in nature: the modulus decreases as the decrement increases, and vice versa. This behavior is characteristic of plastic deformation, where the elastic modulus decreases (and the decrement increases) with an increase in dislocation density [10,12].

The microplastic flow stress determined at $\varepsilon_d = 6.0 \cdot 10^{-8}$ for SMC samples is, on average, almost 1.5 times lower than for MC titanium (Fig. 3), which is indicative of a lower resistance to initial plastic deformation in the case of ultrafine grains (despite the higher yield strength under quasi-static loading).

The nature and possible mechanisms of evolution of elastic and microplastic properties of technically pure titanium (VT1-0 alloy) in microcrystalline and submicrocrystalline states under cyclic loading (fatigue testing) were established. The obtained data revealed significant differences in behavior of two types of structures.

In the MC state, Young's modulus varied non-monotonically, which is associated with the generation of high internal stresses. This non-monotonic change subsequently gives way to modulus reduction due to the prevalence of the process of accumulation of microdiscontinuities. In the SMC state, the elastic modulus decreases significantly already at the first stages of loading, remaining virtually unchanged at subsequent stages. The key factor influencing the elastic modulus in the SMC material is the reduction in density (loosening), which is more profound than in the MC state. This is apparently attributable to a higher concentration of nucleating nanopores in the SMC state.

Thus, the acoustic studies of microplastic properties revealed that, despite the high static strength, SMC titanium is characterized by an earlier and more intense growth of microdamage (micro- and nanoporosity) under cyclic loading than MC titanium. The obtained data are important for predicting fatigue life in development of ultrafine-grained and nano- and submicrocrystalline titanium alloys with an optimized set of mechanical properties.

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Conflict of interest

The authors declare that they have no conflict of interest.

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