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Elastic properties of the titanium alloy Ti-6Al-4V

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The manuscript presents the results of the measurements of Young's modulus (E) for the two-phase titanium alloy Ti-6Al-4V. The estimation of E was made using two independent methods: standard mechanical tests (tensile test) on an Instron electronic dynamometer and the method of nanoindentation using a Nanoscan3D nanohardness-testing scanning machine. The elastic properties were studied for different structural states of the titanium alloy Ti-6Al-4V: nanostructured (NS), microcrystalline (MC) and coarse-grained (CG). The elastic moduli for α- and β-phases were measured by means of the nanoindentation method. It is shown that the value of E for the Ti-6Al-4V alloy in the CG state is smaller than in the NS state by more than 20%, which is likely to be attributed to a change in the amount ratio between α- and β-phases characterized by different elastic properties.

Keywords: titanium alloy Ti-6Al- 4V, Young's modulus of elasticity, nanostructure, nanoindentation, α- and β- phases

1. Introduction

The structural sensitivity of the elasticity modulus for the two-phase titanium alloy Ti-6Al-4V has been insufficiently explored until the present time. Meanwhile, there is a widespread opinion that Young's modulus (E) is the structural insensitivity of metals [1,2]. In this context, this issue requires an actual detailed study, in particular with regard to the structural titanium alloy Ti-6Al-4V in its different structural states.

According to the current concepts, promising for the use as a structural material in aeronautical engineering are nanostructured alloys, in particular, the titanium alloy Ti-6Al-4V [3—8]. Nanostructured semi-products from the two-phase Ti-6Al-4V alloy exhibit increased static and cyclic strength and higher wear resistance. Contrariwise, it is well known that in single-phase nanostructured alloys the modulus of elasticity is noticeably reduced [9—10].

The aim of the our work is to carry out experiments for an estimation, by independent methods, of the normal Young's modulus (E) for the two-phase titanium alloy Ti-6Al-4V in different structural states and a divided estimation of E for each phase in the equilibrium state of the titanium alloy Ti-6Al-4V after annealing.

2. Material and experimental procedure

The object of study is the two-phase $\alpha+\beta$ titanium alloy Ti-6Al-4V in the nanostructured (NS), microcrystalline (MC) and coarse-grained (CG) states. The chemical composition of the alloy completely corresponds to GOST 19807—91, as the Russian alloy VT6. The $(\alpha+\beta) \rightarrow \beta$ transformation temperature was 1253 K for the two-phase Ti-6Al-4V alloy used in our study.

For the initial sample, the alloy in the NS state was taken, produced by multiple isothermal forging at a temperature of 873 K [3] followed by isothermal rolling at a temperature of 823 K. The average grain size (d) of the NS state was 0.18 μm. The MC and CG states was obtained by vacuum annealing of the NS state at a temperature of T=1173 K (1 hour) and T= 263 K (0.5 hours), respectively, the average grain size in the MC state was 5 μm and in the CG state 103 μm (β-transformed grain). Also, a low-temperature annealing was performed on the NS sample at T=773 K (1 hour) for the internal stress relaxation of the initial NS alloy. At the same time, a slight growth of grains to an average of 0.21 μm was observed.

Young's modulus E was determined by two independent methods. Mechanical tensile tests were carried out on an Instron electronic dynamometer in accordance with GOST 11701—84 on flat samples with dimensions of the gage portions 130×12.5×0.75 mm^3, the tension speed was 2 mm/min. Elastic deformation was measured using an extensometer with a base of 100 mm. The tension was performed at room temperature. Another method — determination of hardness and elastic modulus by indentation — is adapted for determining the mechanical properties at the micro- and nano-level [11]. An experiment to determine Young's modulus for each phase was integrally performed with a NanoScan-3D scanning nanohardness tester on the electro-polished CG samples with a size of 12×10×0.75 mm^3 produced from the NS alloy annealed in a vacuum at a temperature of 1263 K.

Structural investigations were carried out on scanning (SEM) and transmission (TEM) electron microscopes JEM — 840 and JEM — 2000EX, respectively. Estimation of the phase composition of the Ti-6Al-4V alloy was

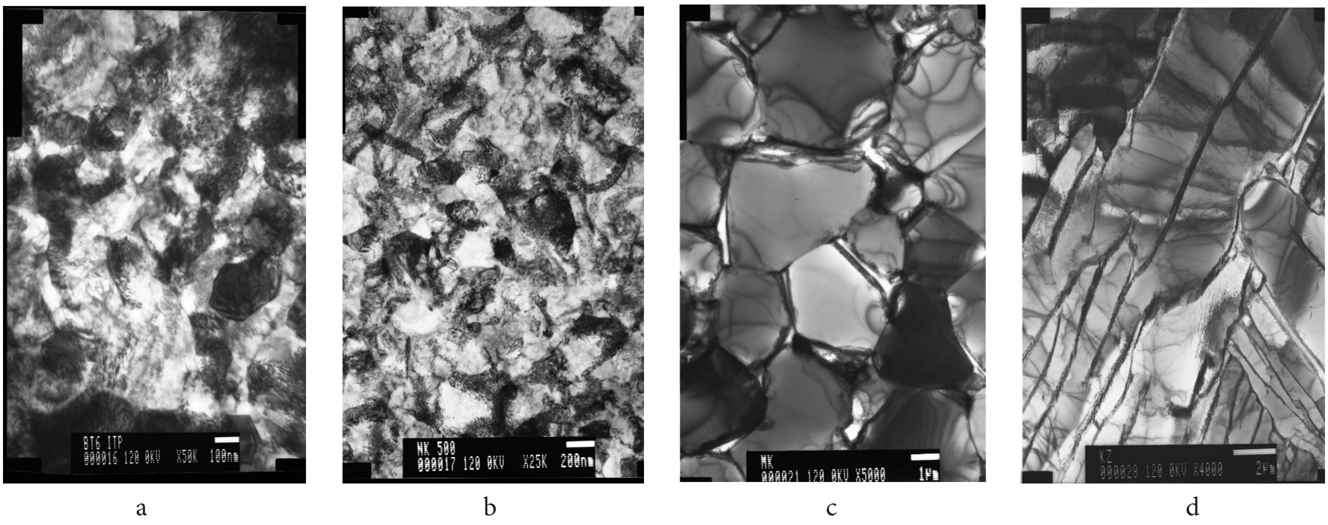


Fig. 1. The structural states of Ti -6Al 4V alloy: a - initial NS state (d=0.18 μm); b - NS state after low annealing at T=773 K (d=0.21 μm); c - MC state (d=5 μm); d - CG state (d=103 μm).

performed by X-ray analysis on a DRON-3 diffractometer. The diffractometer was operated in the following mode: voltage — 40 kV, current — 30 mA, radiation — Cu. The processing results were evaluated with help of the *X*-Ray program.

3. Results and discussion

The fine structure of the investigated alloy Ti-6Al-4V in different structural states, taken on a transmission electron microscope is shown in Fig.1. The alloy in the initial NS state (Fig.1a) has a high internal stress as evidenced by the presence of extinction contours. The NS state obtained after low-temperature annealing at T=773 K (Fig.1b) demonstrates a partial relaxation of internal stresses. In the MC state (Fig.1c) the structure consists mainly of the primary α-phase and slightly of β-phase separation. The CG state (Fig.1d) shows a lamellar structure, where in the matrix the α-phase stands out with the β-phase plates between the α-phase.

According to the results of *X*-ray analysis, the phase composition of the investigated titanium alloy Ti-6Al-4V was determined (Fig.2). In the initial NS state the content of the α-phase is maximum, low-temperature annealing at a temperature of T=772K has almost no effect on the change in the volume ratio of the α-phase and the β-phase in the alloy. Thus, the initial NS and low-temperature annealed states have the identical quantitative phase ratio. Annealing of alloy in the initial NS state at T= 173 K for one hour is followed by an increase in the quantity of the β-phase, and consequently, a reduction in the quantity of the α-phase. After annealing of the alloy at T_{pt}=1253 K for half an hour, one can see an even greater increase in the quantity of the β-phase.

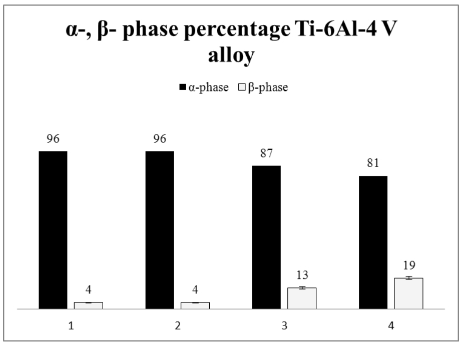


Fig. 2. Phase percentage distribution for each structural state: 1 – (d=0.18 μm); 2 – (d=0.21 μm); 3 – (d=5 μm); 4 – (d=103 μm).

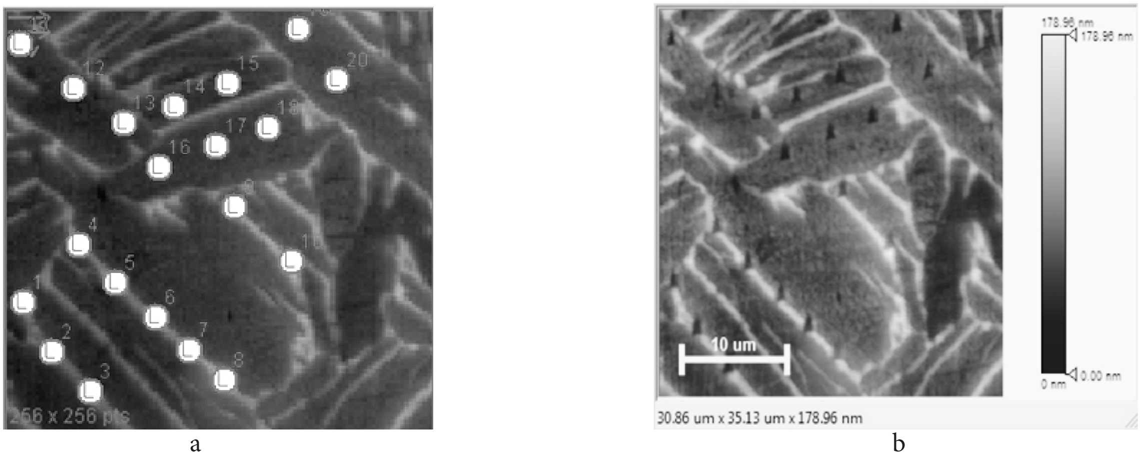
Table 1 shows the values of the elastic modulus of the titanium alloy Ti-6Al-4V in different structural states. The modulus of elasticity was determined from the results of mechanical tensile tests performed on an Instron electronic dynamometer, marked as E_{ins}, as well as by indentation on the NanoScan-3D scanning nanohardness testing machine, designated as E_{nsc}. The value of the normal modulus of elasticity of the investigated titanium alloy Ti-6Al-4V after the transition from the NS to CG states has decreased by more than 20%. One possible reason for this non-trivial

Table 1. The values of the normal elastic modulus E for the Ti-6Al-4V alloy obtained from the results of measurements using Instron and NanoScan - 3D

Grain size, μm	E_{ins}, GPa	E_{nsc}, GPa
0.18	117.4	117.3
0.21	107.8	116.7
5	106.4	109.2
103	95	89.4

Table 2. The modulus of elasticity E for the α- and β-phases in the Ti-6Al-4V alloy (CG state)

Phase	E, GPa
α	92.8 ± 10.6
β	75.8 ± 12.9



a

b

Fig. 3. (a) – a map of indentation of the sample for estimation of the modulus of elasticity in the *α*- and *β*-phases in the Ti-6Al-4V alloy; (b) – sample surface after indentation.

result can be a different volume ratio of *α*- and β-phases in the Ti-6Al-4V titanium alloy in different structural states. Indeed, as evidenced by the results of the experiment, the elastic property E of each phase (*α* and *β*- phases) considered separately in the Ti-6Al-4V alloy differs significantly (Table 2).

The modulus of elasticity E for the *α*-phase is about 22% higher than for the *β*-phase. Similar results for the Ti-6Al-4V alloy have been recently obtained in the work [12].

The modulus of elasticity was determined on a sample in the CG state (Fig.3). Indentation was performed in 10 points for each phase, where indents 1—10 are located in the *β*-phase and indents 11—20 are in the *α*-phase. The load was 5 mN. The data shown in Fig.2 and Tables 2 and 3 indicate the existing dependence — the larger is volume fraction of the *α*-phase in the Ti-6Al-4V alloy, the higher is the normal modulus of elasticity.

4. Conclusions

As result of studying the elastic properties of the Ti-6Al-4V alloy, the following has been revealed:

1) The structural evolution in the Ti-6Al-4V alloy from the NS to CG states promotes a decrease in the modulus of elasticity E by more than 20%.

2) The modulus E for the α-phase in the *β*-field of the annealed Ti-6Al-4V alloy is significantly (by 22%) higher than for the *β*-phase.

3) One of the main causes for the variation of the elastic modulus E for the two-phase titanium alloy Ti-6Al-4V may be changes in the volume fraction of *α*-phase.

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