

## Effect of electron beam treatment on structural change in titanium alloy VT-0 at high-cycle fatigue

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**Abstract.** Changes in the surface of the fractured structure of commercially pure titanium VT1-0 under treatment by low-energy high-current electron beams and the subsequent cycle fatigue to the failure were analyzed by transmission scanning and transmission electron diffraction microscopy. The increase in the fatigue life of samples in 2.2 times after treatment by electron beams was established. An assumption was made that the increase in the fatigue life of titanium, grade VT1-0, was due to the formation of a lamellar substructure conditioned by high-velocity crystallization of the titanium surface layer.

### 1. Introduction

With the development and improvement of technology the materials requirements are constantly tightening. They are defined, in particular, by the desire to improve the components operating temperatures, the realized velocities of movement and transmitted pressures in the movable matings of machines and simultaneously to reduce the weight of parts per unit of power. In some cases, the use of conventional structural steels and alloys cannot meet these complex requirements. In addition, the creation of new volumetric alloyed materials, which is still the main method of increasing their reliability and durability, is becoming increasingly problematic due to the scarcity and high cost of alloying elements [1-7].

In this regard, it is economically and technically feasible to provide structural strength due to surface hardening by creating microlayers with the modified structural-phase state in accordance with the operational requirements. For this purpose, in recent years, the concentrated energy flows are widely used. They can significantly reduce the processing time, which in some cases makes it possible to embed the appropriate equipment into a unified manufacturing technology, as well as reduce the energy costs for treatment due to the fact that only those parts which require hardening and protection are exposed to the concentrated energy flows [8].



In our previous works [9-11] we conducted a study to determine the influence of treatment by electron beams on the fatigue life of steels of different structural classes, and silicon-based alloys. The regularities of the formation and evolution of the phase composition and defect metals substructure were identified. The present paper is a continuation of the previous studies. Its purpose is to examine the fracture surface, phase composition and state of dislocation substructure of commercially pure titanium of grade VT1-0 destroyed in the result of fatigue tests.

## 2. Materials and methods

As a research material samples of commercially pure titanium VT1-0 were used (up to 0.18 Fe; up to 0.07 C; up to 0.04 N; up to 0.1 Si; up to 0.12 O; up to 0.004 H; 0.3 other impurities; remainder Ti, mass %) [12]. The fatigue tests were carried out in a special unit according to the scheme. The samples with dimensions  $120 \times 12 \times 4 \text{ mm}^3$  were produced in accordance with the State Standards (GOST) 25.502-79 and had a symmetrical stress concentrator with 20 mm in radius. The minimal thickness of the sample in the area of stress concentrator was 5 mm. The testing temperature – 300 K, the frequency of bending loading was 10 Hz at a load of 20 MPa. Irradiation of the sample surface, prepared for fatigue testing, was carried out on the unit “SOLO” [13] with the following parameters: the electron energy 16 keV; pulse repetition rate  $0.3 \text{ s}^{-1}$ ; duration of the beam electron pulse 150  $\mu\text{m}$ ; density of electron beam energy  $25 \text{ J/cm}^2$ ; quantity of impact pulses – 3.

The investigations of the fracture surface were carried out by scanning electron microscopy (Tesla BS-301). The analysis of the phase composition and condition of the material defect substructure was performed by transmission electron diffraction microscopy (JEM-2100). Foils for research were prepared by ion thinning of blanks, cut by electric spark method from the sample parallel to the fracture surface as close to it as possible.

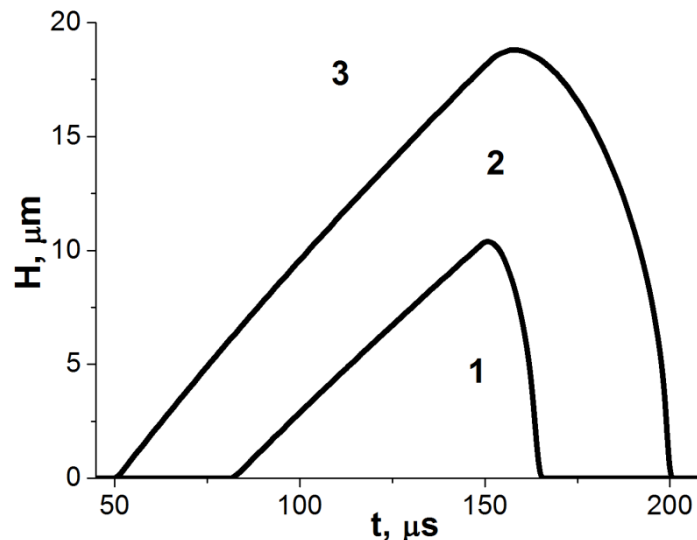
## 3. Results and discussion

High-cycle fatigue testing of samples from commercially pure titanium VT1-0 revealed a significant increase in the fatigue life of the material irradiated by intense pulse electron beam of submillisecond exposure duration (16 keV,  $25 \text{ J/cm}^2$ , 150  $\mu\text{sec}$ , 3 pulses,  $0.3 \text{ sec}^{-1}$ ). Namely, we detected an excess (relative to the non-irradiated samples) of fatigue life of the material in average by  $\approx 2.2$  times. Obviously, this effect is associated with the transformation of the structure of titanium surface layer in the conditions of high-speed heating and cooling caused by electron beam irradiation.

Simulation of thermal processes occurring in the surface layer of metals and alloys under the influence of electron beam showed that exposure of the material surface to the electron beam of micro- and submillisecond duration makes it possible to realize the conditions of ultra-high heating rates (up to  $10^8 \text{ deg/sec}$ ) of the surface layer to the melting temperature and evaporation, and to form in the surface layer a temperature gradient  $10^7$ - $10^8 \text{ deg/m}$ , providing cooling of the surface layer due to heat removal into the cold volume of the material at a rate up to  $10^7 \text{ deg/sec}$  [14]. As a result of this impact in the surface layer within the time interval of a single irradiation pulse the conditions for the formation of non-equilibrium state are created that allows submicro- nanostructured multiphase structures to be registered, which are characterized by properties, unrealizable via the conventional methods of treatment. [13]

The numerical solution of the problem of finding the temperature field [15], which is formed in the surface layer of titanium irradiated with an intense electron beam allowed the thickness of the modified layer to be estimated, as well as the maximal temperature which can be achieved on the exposed surface, the temperature gradient, the heating and cooling rates, time period of existence of the material in different aggregate states. The thermal conductivity equation is solved using the finite difference method [16]. Thermal characteristics of titanium were taken from [17]. The thickness of the surface layer for thermal calculations  $d = 0.5 \cdot 10^{-3} \text{ m}$ , the observation period – 600  $\mu\text{sec}$ . The calculations were performed for the intense electron beam with energy density  $25 \text{ J/cm}^2$  and pulse duration 150  $\mu\text{sec}$ . It was shown that titanium irradiation at a single-pulse mode by the electron beam at the parameters described above leads to the melting of the surface layer with thickness 18.1  $\mu\text{m}$

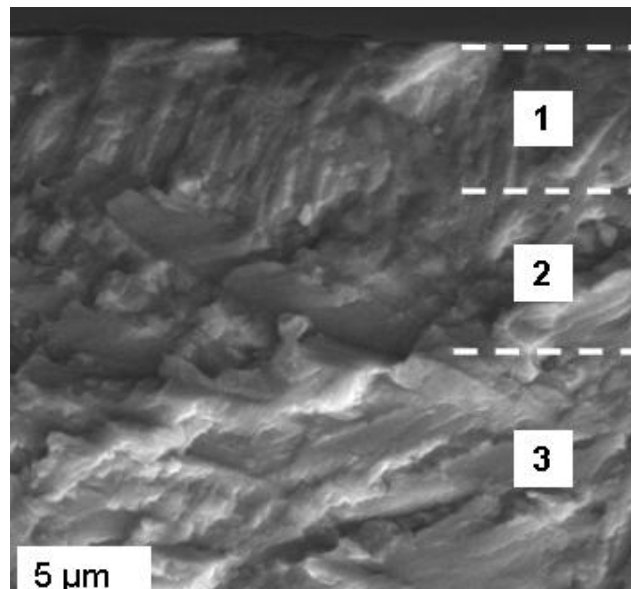
(Figure 1). This layer is divided into two sublayers: the surface layer, thickness  $10.4\ \mu\text{m}$ , which is a single phase layer (liquid) (Figure 1, layer 1.) and the intermediate layer, thickness  $7.7\ \mu\text{m}$ , which is a two-phase layer (liquid + solid state) (Figure 1, layer 2). The lifetime of the first layer is  $80\ \mu\text{sec}$ ; the time interval from the start of titanium melting to its complete crystallization is  $147.2\ \mu\text{sec}$ .



**Figure 1.** Thickness dependence of layer 1 (liquid) and layer 2 (solid + liquid phase) on the observation period during irradiation of the titanium surface by electron beam having an energy density  $25\ \text{J}/\text{cm}^2$  (pulse duration  $150\ \mu\text{s}$ ); zone 3 – zone of the solid phase (the layer of heat influence).

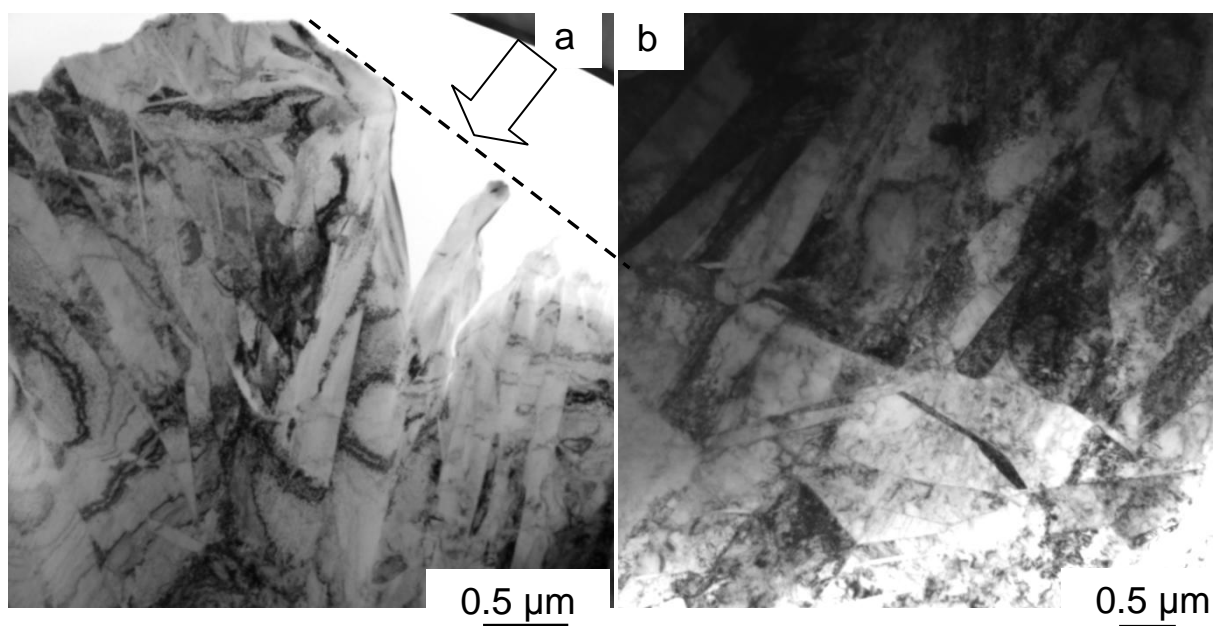
Study on the surface morphology, formed as a result of fatigue tests to fracture of commercially pure titanium, irradiated by electron beam, allowed the thermal calculations to be validated. It was found that part of the sample adjacent to the surface of the electron beam irradiation had a multilayered structure: surface layer (thickness:  $9.5\ \mu\text{m}$ ) (layer 1 in Figure 2) and the intermediate layer (thickness  $10\ \mu\text{m}$ ) (layer 2 in Figure 2). The surface layer has a columnar structure, which apparently indicates a greater crystallization rate of titanium. From the analysis of Figure 2 it follows that layer 1 appeared in connection with the melting and high-speed crystallization of single-phase state, and layer 2 is a layer formed during the crystallization of the two-phase state of titanium.

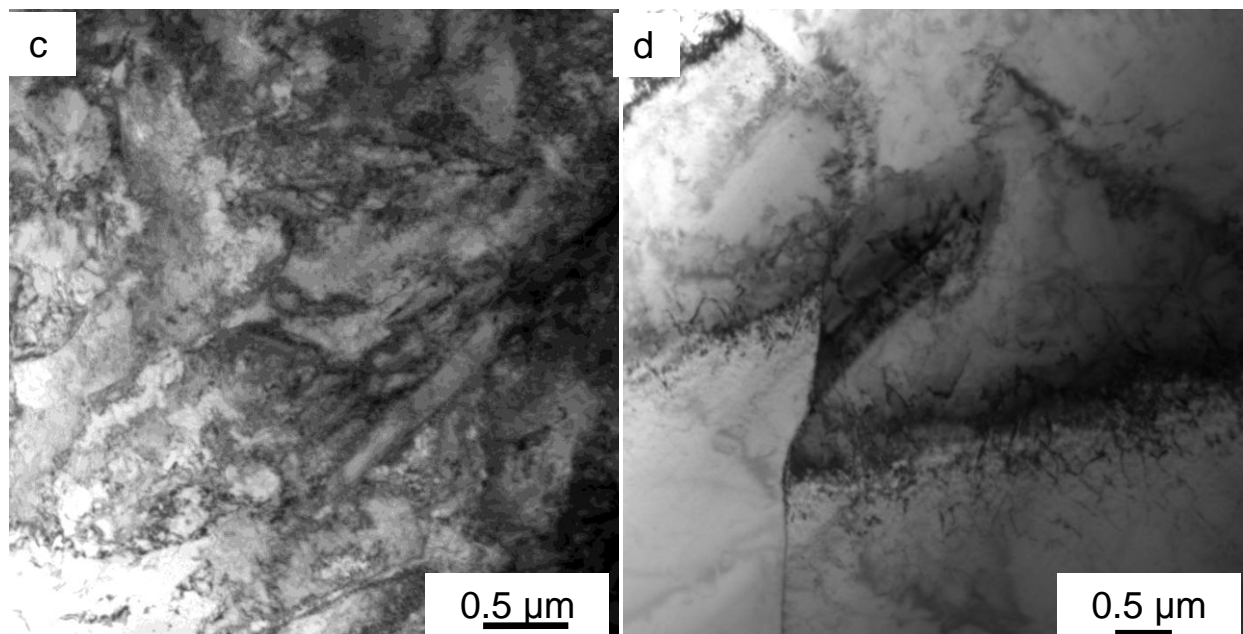
Phase composition and the defective substructure of the surface layer destroyed during the fatigue tests of VT1-0 titanium samples and previously irradiated by an intense electron beam were analyzed by transmission electron diffraction microscopy of thin foils. In parallel with the irradiated samples the fractured titanium samples in the initial state were subjected to the electron microscopy studies. As a result of the research, it was found that the commercially pure titanium in the initial state is a polycrystalline aggregate. After the fatigue tests we observed the dislocation substructure represented by randomly distributed dislocations or dislocations, forming an irregular reticular substructure. The scalar dislocation density was  $2.8 \cdot 10^{10}\ \text{cm}^{-2}$ . The same dislocation substructure was detected in the grain volume of commercially pure titanium in the surface layer and in the layer located at a distance of  $150\text{--}200\ \mu\text{m}$  from the treated surface.



**Figure 2.** The surface of titanium fracture after electron-beam treatment.

The structure of the surface layer of commercially pure titanium VT1-0 after electron beam treatment and high-cycle fatigue is significantly different from the structure of the material in the initial state. The surface layer with thickness of 10 μm has a lamellar structure (Figure 3a). The plates  $\alpha$ -Ti, are generally located at the angle of 70-90° to the irradiated surface. As the distance from the irradiated surface increases the laminae are randomly located in relation to the exposed surface. At a depth of 12-15 μm with lamellar structure we found a subgrain structure (Figure 3b), which is the main type of structure of the material in the layer located at a distance of 30-40 μm from the irradiated surface (Figure 3c). The grain structure close to the structure of the non-irradiated samples after their destruction was detected at a depth of 80 m (Figure 3d).





**Figure 3.** Electron microscope image of titanium structure, grade VT1-0, subjected to electron-beam treatment and fatigue tests up to sample destruction.

Comparing the results of thermal calculations and information obtained by means of electron diffraction microscopy of thin foils, we can conclude that the surface layer of a lamellar structure was formed as a result of the titanium crystallization from a single-phase state; the sub-layer located below with a mixed structure was formed during the crystallization of the two-phase state. Deeper layers should be attributed to the heat affected zone.

#### 4. Conclusions

The treatment of commercially pure titanium VT1-0 by intense pulsed electron beam of submillisecond duration (16 keV, 30 J/cm<sup>2</sup>, 150 μsec, 3 pulses, 0.3 s<sup>-1</sup>) was performed. Fatigue life tests of samples from commercially pure titanium VT1-0, irradiated by intense pulsed electron beam, and non-irradiated samples were carried out. After fatigue tests of samples subjected to electron beam treatment, an increase in fatigue life was established which is on average in 2.2 times higher in comparison to the samples without treatment. The studies of the fracture surface and defect substructure destroyed during fatigue tests of samples from commercially pure titanium were performed. It showed that electron-beam processing of titanium leads to the formation of multilayer structure.

The layer adjacent to the irradiated surface has only a lamellar structure; the following layer has a mixed structure represented by laminas and subgrains. The layer located at a distance (30-40) μm from the irradiated surface has, mainly, a subgrain structure. Numerical calculations of the temperature field, which is formed in the titanium surface layer irradiated by the intense electron beam, were made. It is shown that the layer with the structure of lamellar morphology, adjacent to the irradiated surface, was formed by a high-speed single-phase crystallization (liquid phase) of titanium; the layer lying beneath with lamellar subgrain structure was formed as a result of a high-speed two-phase crystallization (liquid phase + solid phase); the layer of subgrain structure is a layer of thermal influence. The physical cause for the multi-fold increase of the fatigue life of commercially pure titanium VT1-0 is the formation of a lamellar substructure due to high-speed crystallization of the titanium surface layer.

## 5. Acknowledgements

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