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EFFECTS OF ENERGY FLUXES ON MATERIALS

Formation of Residual Stresses in the Surface Layers of Titanium Alloy Targets Irradiated with High-Current Pulsed Electron Beams

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Abstract—X-ray diffraction analysis, optical metallography, and transmission electron microscopy demonstrated that irradiation with high-current pulsed electron beams in the melting mode leads to formation of residual compressive stresses and a finely dispersed globular-lamellar microstructure (the α, α', and α'' plates being oriented parallel or nearly parallel to the surface) in the near-surface layer of samples of VT6 and VT8 alloys up to 20 μm thick. These phenomena are expected to increase the fatigue strength of the material during bending tests. Meanwhile, residual tensile stresses are formed on the surface of samples of VT9 alloy at any energy density of electron beams; vacuum annealing is required to remove these stresses.

Keywords: electron-beam treatment, compressor blades, transmission electron microscopy, X-ray analysis, residual stresses

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INTRODUCTION

The effect of the modes of electron-beam and post-irradiation thermal treatment on performance properties of blades made of α + β-titanium alloys VT6, VT8, and VT9 was studied in [1]. It was found that treatment with high-current electron beams (HCEBs) in a Geza-1 accelerator [2] at electron density of 115–120 keV, energy density of 18–20 J/cm^2, and number of pulses >2 enhances the following properties of the blades: endurance limit (by 10–40%), erosion resistance (more than twofold), heat resistance (more than threefold), and resistance to hot salt corrosion (more than fourfold) [1]. However, the reasons for the observed changes in properties are still unclear, although it seems most reasonable that the strength properties of manufactured articles mostly depend on residual stresses emerging upon electron-beam treatment.

In this connection, we studied residual stresses in recrystallized material of the surface layer of articles made of titanium alloy irradiated with high-current electron beams in the melting mode.

EXPERIMENTAL

Samples 4 mm thick and 26 mm in diameter cut from VT6, VT8, and VT9 alloy rods were used as study objects. These alloys are usually utilized to manufacture commercial blades of the RD33 turbojet engine fan. The chemical composition and the modes of thermal treatment of the alloys are described in [3, 4].

VT6 alloy samples (0.1 C, 6.0 Al, 4.5 V, 0.05 N, 0.15 O, 0.015 H) were annealed at 960°C for 2 h, air-cooled, and subjected to aging in air at 550°C for 4 h.

VT8 alloy samples (0.2 C, 5.9 Al, 3.7 Mo, 0.18 Fe, 0.28 Si, 0.1 N, 0.15 O, 0.004 H) were annealed at 920°C for 1 h, air-cooled, and subjected to aging in air at 550°C for 4 h.

VT9 alloy samples (0.1 C, 6.9 Al, 3.8 Mo, 0.25 Fe, 0.35 Si, 2.5 Zr, 0.05 N, 0.15 O, 0.015 H) were annealed at 960°C for 2 h, air-cooled, and subjected to aging in air at 550°C for 4 h.

The targets were irradiated with high-current electron beams [1, 2] in a Geza-MMP accelerator at an electron energy of 120 keV, pulse duration of 30 μs, and energy density of the electron beam ranging from 16 to 30 J/cm^2. The cross-sectional area of the electron beam was 80 cm^2; the heterogeneity of the energy density distribution over the cross section was less than

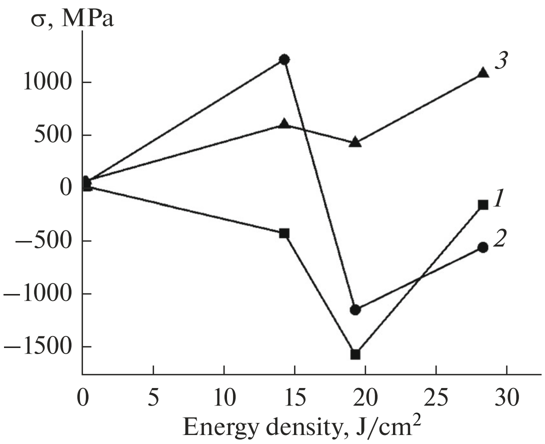

Fig. 1. Residual stresses formed on the surface of targets made of (*1*) VT6, (*2*) VT8, and (*3*) VT9 alloys after irradiation with high-current pulsed electron beams with different energy densities.

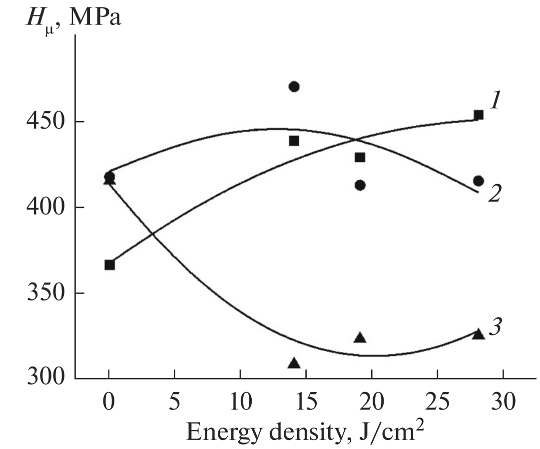

Fig. 2. Microhardness of targets made of titanium alloys after irradiation with high-current pulsed electron beams with different energy densities: (*1*) VT6, (*2*) VT8, and (*3*) VT9.

10%. After irradiation, thin films were prepared mechanically, chemically, or electrochemically from the targets for TEM microstructural studies in the bulk of samples and in recrystallized layers at different depths [3]. The structural studies were also performed by X-ray diffraction (XRD) analysis in Bregg–Brentano geometry, X-ray microanalysis, and optical metallography after layer-by-layer manual fine polishing and chemical etching.

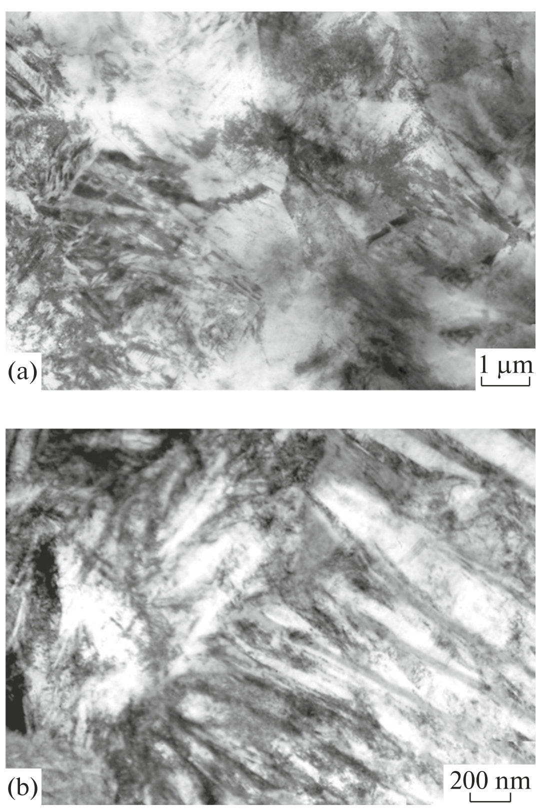

Fig. 3. TEM images of the microstructure of (a) VT9 and (b) VT6 alloys at a depth of 6 μm from the surface irradiated with high-current pulsed electron beam (energy density of 18–20 J/cm^2).

RESULTS AND DISCUSSION

The data on the effect of treatment with high-current electron beams on residual stresses, microhardness, and the structure of titanium alloys are shown in Figs. 1–4. The data on changes in the level of residual stresses (Fig. 1) correlate well with the results obtained by measuring the microhardness on the target surface after irradiation (Fig. 2). One can see that irradiation of the targets made of VT8 and VT6 alloys with the electron beam with energy density <20 J/cm^2 leads to formation of residual compressive stresses and increases the microhardness (in other words, it results in strengthening of the material in the surface layer).

Meanwhile, irradiation of the samples made of VT9 alloy leads to formation of residual tensile stresses, thus reducing microhardness. This effect is observed at any energy density of the electron beam. In order to recover the original properties of the samples made of VT9 alloy, the irradiated targets need to be annealed under vacuum.

Figure 3 shows the photomicrographs of the structure of the targets made of VT6 and VT9 alloys at a depth of 6 μm from the irradiated surface. The full thickness of the recrystallized zone is 15 μm. Figure 4 shows the photomicrographs of the structure of irradiated alloys. One can see that a globular-lamellar structure is formed in the VT6 alloy during recrystallization, while a needle-like structure is formed in the VT9 alloy.

These findings, as well as the results of structural studies [3, 5] obtained earlier, show a good correlation between the changes in the structure and strength

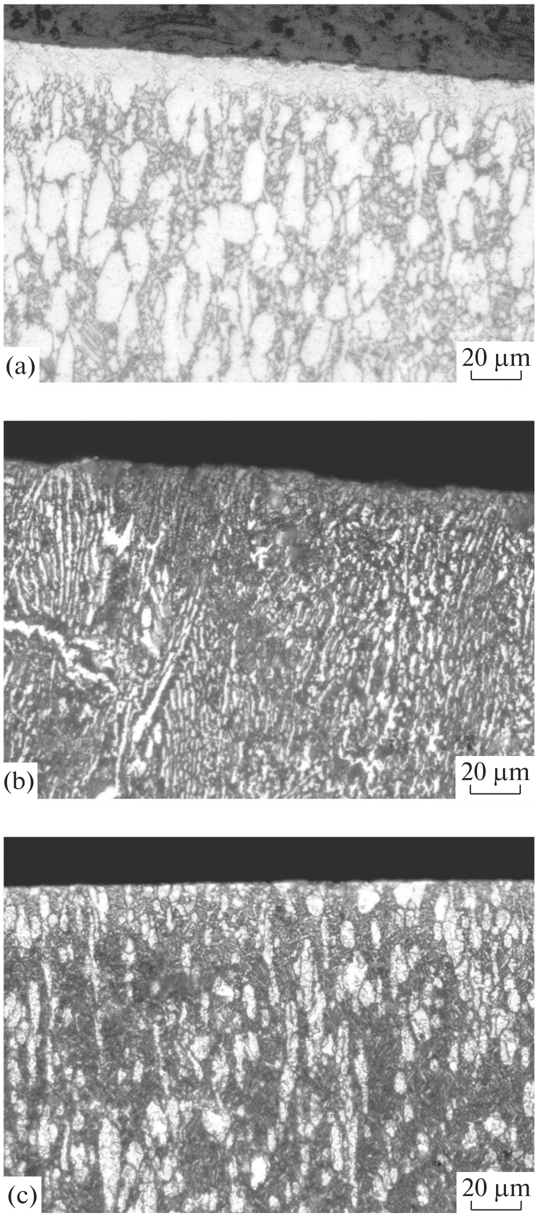

Fig. 4. The microstructure of the surface layers of (a) VT6, (b) VT8, and (c) VT9 alloys after irradiation with high-current pulsed electron beam (energy density of 18–20 J/cm^2).

properties of titanium alloys irradiated with high-current electron beams and formation of various residual stresses in these alloys.

CONCLUSIONS

X-ray diffraction analysis, optical metallography, and transmission electron microscopy were used to show that irradiation with high-current electron beams in the melting mode leads to formation of residual compressive stresses and a finely dispersed globular-lamellar microstructure (the α, α', and α'' plates being oriented parallel or nearly parallel to the surface) in the near-surface layer of the VT6 and VT8 alloy samples up to 20 μm thick. These phenomena are expected to increase the fatigue strength of the material during bending tests. Residual tensile stresses are formed in the surface layers of VT9 targets at any energy density of electron beams; vacuum annealing is required to remove these stresses.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

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