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Gradient Structure Formed in Commercially Pure Titanium Irradiated with a Pulsed Electron Beam

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Abstract. The paper reports on a study of commercially pure VT1-0 titanium irradiated with a submillisecond intense low-energy pulsed electron beam: electron energy 16 keV, pulse repetition frequency 0.3 Hz, pulse duration 150 µs, energy density 25 J/cm^2, and number of pulses $N = 3$. The composition of VT1-0 titanium (up to mass %): 0.18Fe, 0.07C, 0.04N, 0.1Si, 0.12O, 0.004H; other impurities 0.3 and the rest being Ti. The study shows that the irradiated material assumes a multilayer gradient structure. The irradiated material represents a polycrystalline aggregate, and its grain substructure depends on the depth from the irradiated surface. Its surface layer 10.4 µm thick reveals a lamellar structure. In its subsurface layer 7.7 µm thick, a subgrain structure with submillimeter crystallite sizes is formed. The heat affected layer assumes a lamellar structure at a depth of 18.1 µm and a grain-subgrain structure at a depth of 50 µm. At a depth of ≥180 µm, the material has a polycrystalline structure based on α-Ti.

INTRODUCTION

Surface treatment by concentrated energy flows is a promising method of increasing the fatigue life of metal materials. For example, such materials, including steels, irradiated with pulsed electron beams display higher values of their wear strength, corrosion resistance, and surface microhardness [1–5]. However, the physical mechanism by which electron beams provide metal surface modification is not quite clear and likely due to insufficient research data on microstructural and phase changes in materials subjected to electron beam treatment. Our studies of different steels and aluminum alloys after low-energy high-current electron beam irradiation [6–9] suggests that this type of treatment improves their fatigue life through changing their structure, phase composition, and dislocation substructure.

Here we analyze the formation of gradient structural states in commercially pure titanium irradiated with a pulsed electron beam. Further research is expected to investigate the influence of this treatment on the fatigue life of titanium.

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MATERIALS AND METHODS

The test material was commercially pure VT1-0 titanium of the following composition (up to mass %): 0.18Fe, 0.07C, 0.04N, 0.1Si, 0.12O, 0.004H; other impurities 0.3 and the rest being Ti. The material was irradiated on the SOLO setup [10, 11] at an electron energy of 16 keV, pulse repetition frequency of 0.3 Hz, pulse duration of 150 µs, and energy density of 25 J/cm^2; the number of pulses was $N = 3$.

The structure of the irradiated material was analyzed in depth by scanning electron microscopy (Tesla BS-301) and transmission electron microscopy (JEM-2100F) for which foils were prepared through ion thinning of plates spark cut from a massive specimen perpendicular to the irradiation surface.

RESULTS AND DISCUSSION

Simulation data shows that when exposed to micro- and submillisecond electron beam irradiation, the surface layers of metal materials and alloys are heated with ultrahigh rates (up to 10^8 deg/s) to supercritical temperatures (melting and evaporation points), which results in maximum temperature gradients (10^7–10^8 deg/m), and are cooled through heat removal into the integrally cold material bulk with a rate of 10^9 deg/s [10–13]. Thus, conditions are established for the formation of nonequilibrium states in the surface layers within a single pulse interval and of submicro- and nanostructures (in some cases, amorphous) with properties unattainable by conventional treatment methods [10–13].

Using numerical methods [14, 15], the temperature field arising in a titanium surface layer irradiated by an intense electron beam was estimated to determine the modified layer thickness, maximal temperature on the irradiated surface, temperature gradient, cooling and heating rates, and time intervals of different aggregate states in the material. According to the temperature field calculations, intense electron beam irradiation provides a multilayer surface structure in commercially pure VT1-0 titanium [16]. The structure and the phase state in these layers were analyzed by diffraction electron microscopy of ion-thinned foils. Their typical image is shown in Fig. 1.

Figure 2 shows images of the zones under study. The zones are in different layers because they are formed under different temperature conditions. Our analysis suggests that the Ti material is a polycrystalline aggregate regardless of the zone and layer but the grain substructure depends on the zone of analysis. In zone *1* (layer *1*), a lamellar grain structure is found. Its lamellae are separated from each other and located mainly at the grain boundaries. They rarely form diverse configurations. In layer *2* (Fig. 2a), a submicrocrystalline structure with a subgrain size of 1–2 µm arises.

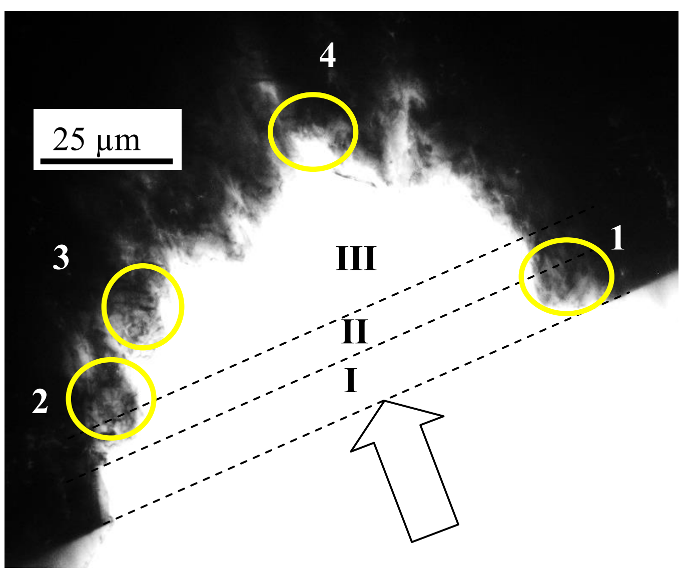

FIGURE 1. Image of Ti foil with indication of layers identified from temperature field estimates: I—single-phase layer (10.4 µm); II—two-phase layer (7.7 µm); III—heat affected layer; arrow—irradiated surface; ovals—zones of detailed analysis

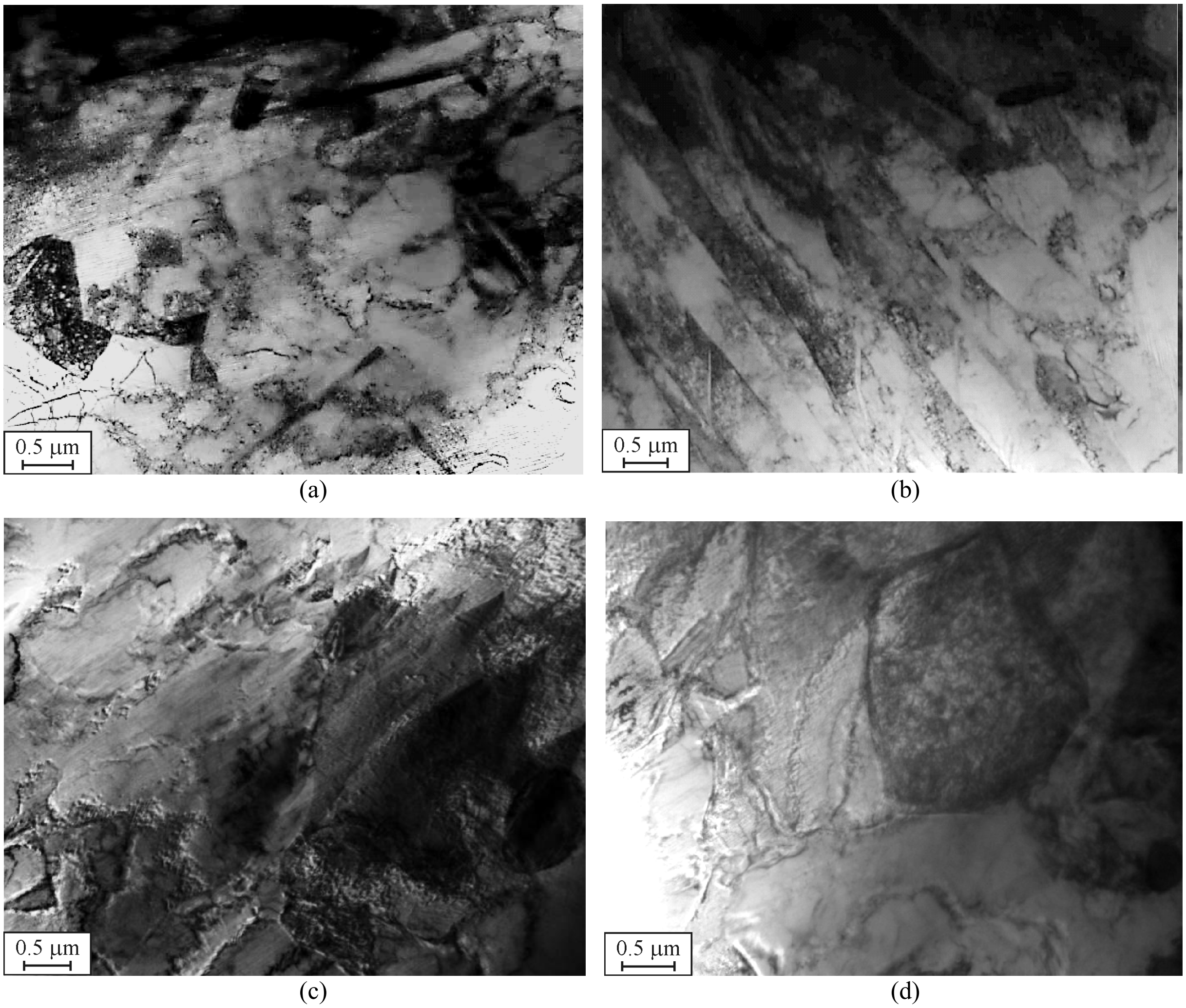

FIGURE 2. Images of structure in zone *2* (a), zone *3* (b), and zone *4* (c, d) shown by ovals in Fig. 1

The structure of the heat affected layer (Fig. 1, layer *3*) depends strongly on the distance to the irradiated surface. The layer adjacent to layer *2* (Fig. 1, zone *3*) has a lamellar structure (Fig. 2b). The layer at a depth of about 50 μm has a grain-subgrain structure (Figs. 2c, 2d). At a depth of 180–200 μm, the material reveals a polycrystalline structure based on α-Ti. In Ti grains, a substructure of chaotically distributed dislocations is identified; the scalar dislocation density ranges to 1.3×10^{10} cm^{-2}.

CONCLUSION

Thus, electron beam irradiation provides substantial structural modification in VT1-0 titanium alloy. According to preliminary calculations, the irradiated material assumes a multilayer structure featuring several states. Our analysis by diffraction electron microscopy suggests that the surface layer of commercially pure VT1-0 titanium irradiated by a submillisecond intense low-energy pulsed electron beam assumes a multilayer state with characteristics dependent on the depth from the irradiated surface. The thickness and the structure of the formed layers vary with depth due to temperature conditions. At a depth of 180 μm (initial state), the material reveals a polycrystalline structure based on α-Ti. Its subsurface layer 10.4 μm thick and its heat affected zone at a depth of 18.1 μm feature a lamellar structure. Its layer 50 μm thick assumes a subgrain structure separating the subsurface layer and the heat affected zone. In the heat affected zone at 50 μm, a grain-subgrain structure is formed.

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