Surface Hardening Alloy VT6 of Electric Explosion and by Electron Beam

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Abstract: The aim is to study the phase composition, structure and properties of the surface layer of the VT6 titanium alloy, subjected to combined treatment, consisting of alloying by the plasma of an electric explosion of a graphite fiber with a charge of the SiC powder and subsequent exposure by a high-intense electron beam. As a result of such treatment, a multiphase surface layer with a submicron and nanosize structure forms with the microhardness manifold exceeding its value in the sample volume are presented.

Keywords: electron-beam treatment, structural-phase states, electric explosion alloying, titanium, scanning and transmission electron microscopy

INTRODUCTION

Titanium and titanium-based alloys are the most in-demand structural materials [1] and various coatings are used for the surface protection of made of them wares [2, 3]. One of the most promising methods of forming coatings is electric explosion alloying [4, 5]. Properties of the surface layer of the material and the ware are additionally improved as a whole after combined treatment uniting the electric explosion alloying and the subsequent electron-beam treatment of the modified surface [5, 6].

The electron-beam treatment has more possibilities for the control and regulation of supplied energy when compared with widespread laser technology. This method is characterized by the local energy distribution in the surface layer of the treated material and high efficiency [7]. Therefore, substantial changes in the structural-phase state of surface layers lead to a significant improvement in physicochemical and strength properties of the material that are unattainable for traditional methods of surface treatment.

MATERIAL AND PROCEDURE OF STUDY

As the modified material we selected VT6 titanium alloy with the composition, wt.%, ≤0.6 Fe, ≤0.1 C, ≤0.1 Si, 3.5–5.3 V, 5.3–6.8 Al, ≤0.3 Zr, ≤0.05 N, ≤0.2 O, ≤0.015 H; the remainder is Ti, which is applied for the production of the large-size welded and built-up structures of aircrafts and for the manufacture of vessels operating under the internal pressure in a wide temperature range and a whole series of other structural elements related by the structure to the class of ($\alpha + \beta$) alloys [9]. The samples were washer-shaped 10 mm thick and 18 mm in diameter.

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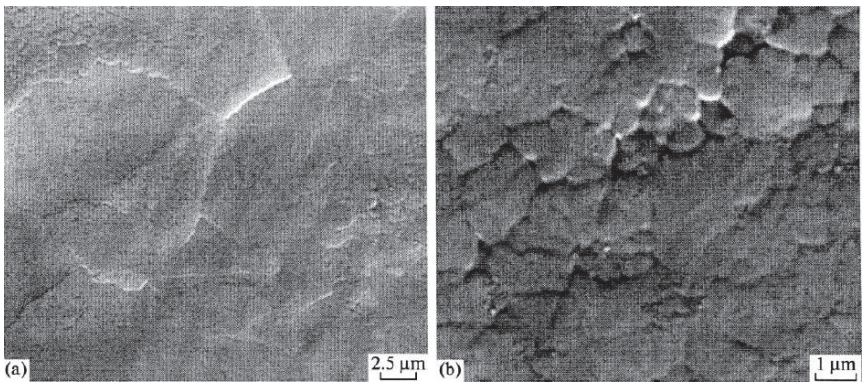


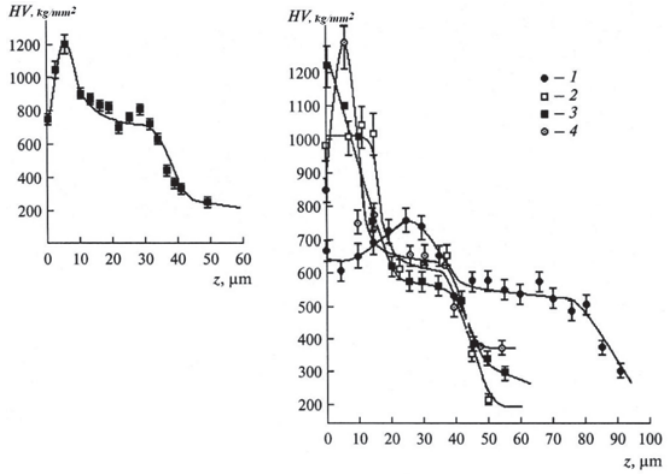
FIGURE 1. Electron microscopic image of the surface structure after electric explosion alloying (CF + SiC) and further electron-beam treatment (scanning electron microscopy). E_s = 45 J/cm^2, τ = 100 μs, z = 10 μm and f = 0.3 s^{-1}

The doping of the surface layer was implemented by the action of plasma formed during the electric explosion of carbon fibers (CF) with the charge of silicon carbide (SiC) powder placed on its surface in the explosion area. The electric explosion alloying mode was as follows: the absorbed power density was 6.5 GW/m^2, the diameter of the accelerator nozzle was 20 mm, the sample distance from the nozzle cut was 20 mm, the weight of carbon fibers was 140 mg, and the powder weight was 50 mg. These conditions correspond to an average thickness of the molten layer of 30 μm in [5, 6].

The additional treatment of the modified layer was implemented by a high-intense electron beam on a SOLO installation [10] according to the following modes: electron energy of 18 keV, electron beam energy density E_s = 45–60 J/cm^2, action pulse duration T = 100 and 200 μs, pulse number n = 10 and 20, and pulse repetition frequency f = 0.3 s^{-1}; the exposure was performed in argon at residual pressure of 0.02 Pa.

Investigations into the elemental and phase compositions and the granular and intragranular structures of the surface layer were carried out by scanning and electron diffraction microscopies [11, 12] and X-ray structural analysis (the Bragg-Brentano geometry and CoK_α radiation). The mechanical properties of the surface layer were evaluated by microhardness measurements.

The surface layer formed after electric explosion alloying, similarly to earlier investigations [5, 6], is characterized by a high level of roughness and a great variety of structural elements (micropores and microcraters, microcracks, buildups, and particles of loosened graphite fibers).



(a) (b)

FIGURE 2. Microhardness distribution over the depth after electric explosion alloying (a) and electron-beam treatment in modes 1–4 (b)

TABLE 1

Mode	E_s, J/cm^2	τ, μs	N, pulse	f, s^{-1}
1	45	100	10	0.3
2	50	100	10	0.3
3	60	100	10	0.3
4	45	200	20	0.3

RESULTS OF STUDY AND DISCUSSION

The further electron-beam treatment is accompanied by a substantial decrease in its roughness (Fig. 1(a)). A polycrystalline structure with grains 10 μm in size is revealed on the surface. A subgranular structure (cells with high-rate crystallization) is observed in the grain volume with the subgrain size in a range of 0.2–0.8 μm (Fig. 1(b)).

Melting of the surface layer by the electron beam and the further high-rate crystallization lead to the formation of a multilayer structure presented by the doped layer proper and the layer of the thermal effect, which gradually propagates into the main volume of the material. The thickness of the doped layer is almost independent of the electron-beam treatment mode and varies in a range from 25 to 30 μm. This layer in depth divides into three clearly pronounced sublayers that we call surface, near-surface and intermediate layers differing in morphology and sizes of the structural elements at an electron beam energy density of 45 and 50 J/cm^2 and action pulse duration of 100 μs. For example, the doping layer preliminary has a globular structure. During treatment with E_s = 60 J/cm^2 and τ = 100 μs, as well as E_s = 45 J/cm^2 and τ = 200 μs, its structure improves and does not divide into sublayers.

X-ray phase analysis of the exposure surface showed that the strengthening zone contains second phases along with α-Ti, the volume fraction of which varies in from 30% to 50%; titanium carbide (TiC) is basic among them.

An analysis of the strength characteristics of the VT6 alloy surface layer, which is based on the construction of the microhardness profile, shows that the maximum of *HV* after the electric explosion alloying is reached in 10- to 12-μm-thick near-surface layer (Fig. 2(a)) and exceeds this value for the base by a factor of 3.5–5.5. The thickness of the surface layer with microhardness threefold greater than for the base reaches 35 μm. Further electron-beam treatment leads to a substantial increase in its value to 85–90 μm (see Fig. 2(b)).

To elucidate the physical nature of an increase in the microhardness of the doped layer, we analyzed foils placed near the treatment surface (2–3 μm) and at a depth of 25 μm by transmission electron microscopy after electric explosion alloying and electron-beam treatment by mode 3 (see the Table 1). The structure of these layers, which was determined by scanning electron microscopy of the metallographic cross section, is represented in Fig. 3(a). Figure 3(b) shows the distribution of silicon in the doped layer, which was revealed by electron probe microanalysis. It is clearly seen that the concentration of Si at the doping surface is 8–10 wt.% and, being monotonically decreased, terminates at the boundary with the thermal influence layer.

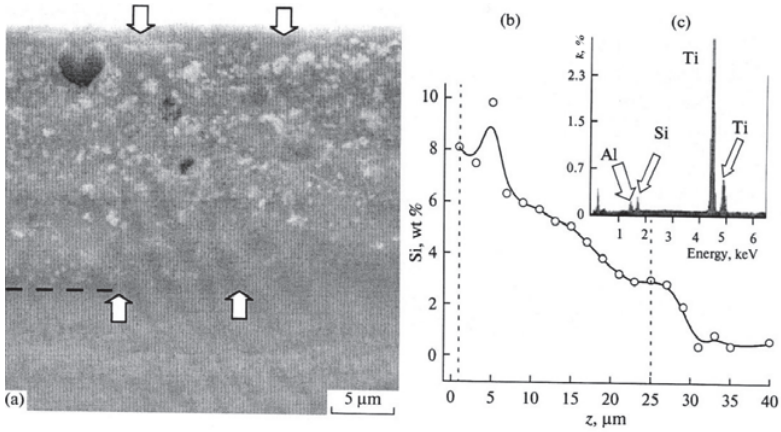


FIGURE 3. Gradient structure over the structure depth and the elemental composition of the combined treatment zone of the VT6 alloy surface. Picture (a) shows the layers, which were investigated by transmission electron microscopy

The subgrain volume reveals a lamellar substructure of α-Ti in the subgrain volume; its plate thickness varies in a range from 50 to 150 μm. Particles of the second phase are placed in the form of extended inter-layers or globules, which are arranged along subgrain boundaries and in boundary junctions. These particles are titanium (TiC) and silicon (SiC) carbides according to data of diffraction microanalysis. The SiC particles are globular-shaped and their sizes vary in a range from 50 up to 100 nm.

Thus, a multiple increase in the microhardness of the strengthening zone of the VT6 alloy after combined treatment is caused by the formation of a multiphase submicron and nanosize lamellar structure based on α-Ti, which is reinforced by particles of titanium and silicon carbides.

A structure similar to abovementioned one also forms in the layer placed at a depth of 25 μm; notably, a granular-subgranular structure with subgrains 350 μm in size on average manifests itself. A lamellar substructure is revealed in their volume (α-Ti; plate thickness varies in a range from 40 to 80 nm). Sub-grains are divided by extended interlayers of the second phase (plate thickness varies in a range from 40 up to 80 nm). The diffraction microanalysis of the structure of this layer revealed strong diffuse scattering in electron diffraction micropatterns, which indicates the lamination of the α-Ti-based solid solution, a high imperfection level of the crystal lattice of α-Ti, and the destruction of the long-range order [12].

CONCLUSIONS

The electric explosion carbonization jointly with particles of the SiC powder forms a strengthened layer 35 μm thick on the surface of the VT6 alloy with the microhardness exceeding the same of the base by a factor of 3–5. Further electron-beam treatment decreases the roughness of the modified surface and leads to an increase in the thickness of the strengthened layer to 85–90 mμ.

A multiple increase in the microhardness of the surface layer of the VT6 alloy subjected to electric explosion alloying and further electron-beam treatment is caused by the formation of the multiphase submicron and nano-size lamellar structure based on α-Ti, which is strengthened by the nanosize precipitates of second phases of TiC and SiC.

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