Investigation of the microstructure and the thermal processes in a Ti6Al4V alloy surface-modified by scanning electron beam

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Abstract. We present a study of the microstructure, the microhardness and the thermal processes taking place in a Ti6Al4V alloy (Ti64) surface-modified by means of a scanning electron beam. X-ray diffraction (XRD), scanning electron microscopy (SEM) and optical metallography were used to characterize the structure and morphology of the samples. A heat model based on solving the heat-transfer equation by Green functions was applied to calculate the temperature fields and depth of the structural changes in the titanium alloy. In particular, the effect was assessed of the scanning beam current during the process of surface modification on the structure and morphology of the layers.

1. Introduction

An important field in the technologies for improvement of the physico-mechanical properties of materials is the surface processing by high-energy fluxes (HEF), such as electron, photonic and ion beams [1, 2]. The surface electron-beam processing alters the chemical composition and microstructure of metals and alloys, thus triggering significant enhancement of their exploitation properties [3, 4]. This is why a number of authors have focused their attention on modification techniques that use a flow of accelerated electrons opening possibilities of the development of materials with new microstructure and novel properties [5-7].

Titanium and its alloys are widely used materials in a variety of industries and in medicine because of their exceptional mechanical, physical and chemical properties combined with biocompatibility. The main drawbacks of these alloys are their poor wear resistance and hardness. One way of increasing the Ti alloys hardness is processing by flows of accelerated electrons. E.g., pulsed [1, 5] and continuously operating electron beams have been applied by scanning the material’s surface along a pre-determined trajectory [2, 4, 8, 9].

In another work [10], the TA15 alloy was processes by a pulsed electron beam. It was found that the treatment resulted in forming three areas in the specimen’s depth: a melted surface film, a heat-affected zone, and a substrate zone. The melted area was characterized by a refined

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microstructure with a grain size of 168 nm. The smaller grain size compared to that of the matrix (310 nm) was the reason of this zone’s improved hardness and wear resistance. The matrix hardness was about 4.62 GPa; after the electron beam treatment it reached a value of 7.11 GPa (53% increase). It was noticed that the depth of melted layer was approximately 25 μm, which corresponded to the hardness gradient in the surface film.

The authors of [11] applied surface electron-beam modification of Ti6Al4V (Ti64) alloy intending to obtain a specific surface topography and enhanced mechanical properties. Both studies [10, 11] revealed a gradient in the microstructure consisting of a melted area near the surface and a heat-affected zone formed after the treatment in the base material. The phase transformations of the typical bimodal structure of the Ti64 alloy produced a mixed α’ (martensite), α and β structure in the heat-affected zone to complete martensite structure in the melted area. The average hardness of the melted and the heat-affected zones was found to be 450 ± 10 HV0.03 and 440 ± 20 HV0.03, respectively. These values were almost 22 – 25% higher than that of substrate (360 ± 32 HV0.03). The improved hardness was a result of the formation of a fine α’ martensite structure during the fast cooling that followed the surface electron-beam modification process.

The main purpose of the present study is to investigate the changes in the phase composition, microstructure, and heat distribution in the surface of Ti6Al4V alloy samples after scanning the surface by an electron beam with different current densities. Using a thermal model, the temperature field distribution and the depth of the structural changes in the Ti6Al4V alloy were determined and compared with the experimental results.

2. Experimental procedures
Specimens with size of Ø 20 × 4 mm were used for the experiments with the following chemical composition: wt % – 5.80 Al; 4.67 V; 0.16 Fe; 0.09 Co; 0.07 Mo; 0.02 Pd; 0.14 Hf; Ti-Bal.

The electron-beam surface modification (EBSM) was carried out on a Leybold Heraeus (EWS 300/15–60) installation. The technological parameters applied were as follow: electron-beam current $I = 20$ and 25 mA, accelerating voltage $U = 55$ kV, sample motion speed $v = 5$ mm/s, electron beam scanning rate $f = 1$ kHz and a circular scanning pattern.

The crystallographic structure of the samples was analyzed by X-ray diffraction (XRD) (URD-6 Seiferd&Co) with monochromatic Cu Kα radiation in a Bragg-Brentano geometry. After Kroll’s reagent etching, scanning electron microscopy (SEM) and optical microscopy images were recorded by a LYRA 1 XMU, Tescan, SEM equipped with an energy dispersive spectroscopy unit (EDS, Quantax 200, Bruker) and a Nikon optical microscope, respectively. The microhardness measurements were conducted on the top of each sample with a load of 100 g and dwell-time of 15 s using a PMT-3 (POMO, Russia) microhardness tester. The distance between the indents was at least 20 μm.

The heat model used for determining the temperature field distribution and the depth of the structural changes was described in detail in [12, 13]. In the numerical simulation, the values used were those of the technological conditions listed above and the thermo-physical parameters ($\alpha = 2.7$ mm$^3$/s, $\lambda = 0.0067$ W/mm K) of the Ti6Al4V.

3. Results and discussion
As shown in the SEM micrograph (figure 1), the initial microstructure of the Ti64 alloy consists of a mixture of α and β grains. In accordance with the metallographic results of the bimodal alloy, the XRD analysis of the sample before the EBSM treatment confirmed the presence of both α-Ti and β-Ti peaks (figure 2).

The phase identification was performed by means of the ICDD Database files PDF #44-1294 and PDF #09-0098 for the α (hcp) and β (bcc) phases, respectively. All diffraction maximums were indexed and all three patterns demonstrated a relatively low background. After the surface modification of the alloy by either 20 mA or 25 mA beam currents, no β-Ti was identified. All diffraction peaks were assigned to α-Ti. Since α’-martensite peaks have a crystal structure similar to α-Ti, peaks corresponding to hcp were only observed. These data are evidence of a β→α transformation occurring during the electron-beam processing.
Figure 1. SEM micrograph of the Ti64 alloy initial morphology.

Figure 2. XRD patterns of the Ti64 alloy before and after the EBSM.

The topography of the treated samples was investigated by optical microscopy and is shown in figure 3. Clear straight grain boundaries of the equiaxed-grained polycrystalline material are seen on the surface of the EBS-modified alloy. The higher beam-current treatment results in the formation of coarser grains. After the rapid solidification, the grains of the alloy treated by 20-mA beam-current exhibit finer α’-martensitic structures, as opposed to the more distinguishable and coarser α’-laths of the 25-mA treated samples.

Figure 3. Optical micrographs of the surface structure of Ti64 alloy after EBSM by a) 20 mA and b) 25 mA beam current. The numbers indicate (1) 100× and (2) 400× magnification.

The depth of the structural changes of the EBS modified Ti64 alloy was determined by numerical calculations following the heat model [12, 13] and drawn in figure 4, where the melting point of the Ti64 alloy is marked. For EBSM by the smaller electron-beam current (20 mA), the depth of structural alterations is found to be $h_{calc}^{20mA} = 400 \, \mu m$. After raising the electron beam current from 20 mA to 25 mA, the zone depth reached $h_{calc}^{25mA} = 500 \, \mu m$. It is clear that the increased depth corresponds to lower temperature values.

To verify the results obtained via the heat model, the depth of the structurally changed zones was evaluated experimentally for both specimens. Thus, cross-section measurements of EBS-modified M samples were performed (figure 5). The microstructure observed near the surface is a result of the rapid solidification; its features correlate with the heat-conduction direction. The results demonstrated that the
experimentally determined depths of structural alterations reached about $h_{exp}^{20mA} = 397 \mu m$ and $h_{exp}^{25mA} = 520 \mu m$ when treated by electron-beam current of 20 mA and 25 mA, respectively. The comparison of the theoretically-calculated (figure 4) and the experimentally-obtained (figure 5) depths of the treated zones shows very good agreement.

The difference between the microhardness values measured on the surface of the processed samples as opposed to the initial microhardness of the Ti64 alloy ($356 \pm 3$ HV$_{0.1}$) is shown in table 1. The results indicate that after EBSM by a beam current of 20 mA, the microhardness increased to $397 \pm 2.97$ HV$_{0.1}$ compared to the sample processed by the higher beam-current (25 mA), where the hardness stayed almost unchanged.

| Electron beam current | 20 mA | 25 mA |
|-----------------------|-------|-------|
| Average depth, [µm]   | 399.83±1.51 | 519.62±5.07 |
| Surface hardness, [HV$_{0.1}$] | 397±2.97 | 356±3.67 |

*Initial hardness of the alloy – HV$_{0.1}$ = 356±3.

Therefore, the larger temperature gradients that occur during processing by the 20-mA beam-current enable a diffusionless transformation to a finer and harder α' martensitic microstructure. Additionally, the surface micro-hardness is improved via the effect of solid-solution strengthening of V after dissolving the β phase into the pre-saturated α'-martensite. The hardness values obtained depend on the process parameters.

Thus, raising the heating temperature results in a coarsening of the alloy grains and, therefore, martensite laths. The coarser lamellar structure obtained at the higher beam-current is a factor lowering the microhardness. However, the residual stresses generated at the surface after EBSM should also be taken into account.

### 4. Conclusions

In this work, the microstructure is discussed of Ti64 samples after processing by a scanning electron beam. The effect is evaluated of the electron-beam current during the treatment. It is found that one can alter the structure and properties of the alloy by way of varying the current density of the electron-beam modification. It is proved that a higher current corresponds to higher grains sizes and a lower surface microhardness. The results from a heat model are in agreement with the experimentally obtained data.

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