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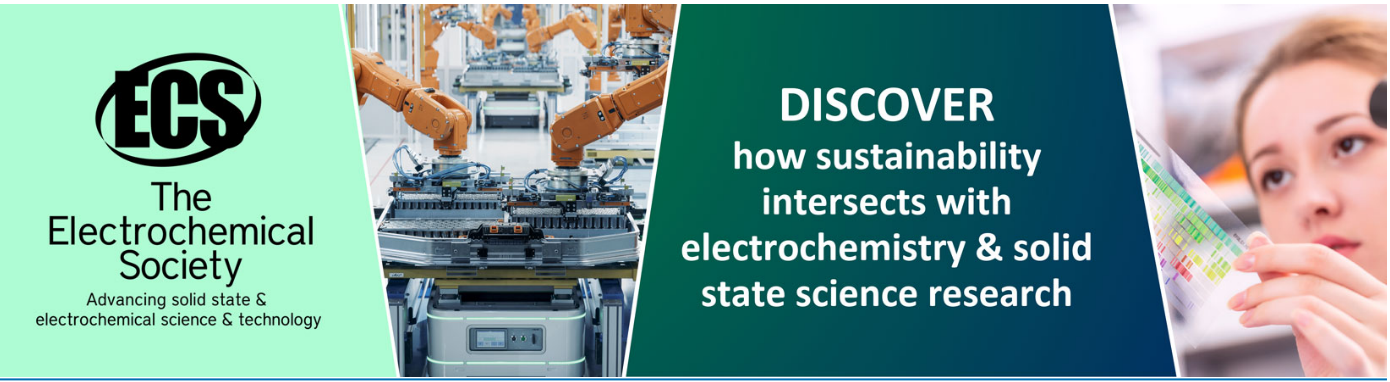

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Scanning electron beam treatment of Ti-6Al-4V titanium alloy produced by casting and EBM processes

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Abstract. The results obtained by studying the surface morphology, microstructure and microhardness of Ti-6Al-4V titanium alloy subjected to scanning electron beam treatment are discussed. It is shown that the surface of titanium parts produced by electron beam melting followed by scanning electron beam post-treatment becomes smoother as compared with the surface of the as-build parts. The occurrence of the martensite α'-phase in the structure of melted surface layer of both Ti-6Al-4V titanium cast alloy and EBM-printed Ti-6Al-4V parts subjected to scanning electron beam treatment is discussed. The latter results in increase the microhardness of the samples under study.

1. Introduction

Nowadays an increasing interest is paid to different additive manufacturing technologies of metal materials followed by their thermomechanical post-treatment [1, 2]. The necessity for carrying out the latter is related to heterogeneous structure of 3D-printed parts, the presence of metastable phases, the emergence of large amount of micropores and flaws induced by fast crystallization, directed solidification and phase transitions, with the latter resulting from repeating thermal cycles.

The methods of continuous electron beam [3] and pulsed current electron beam treatments [4] can be effectively used as thermal post-processing techniques of 3D-printed titanium components. In particular, simultaneous radiation, heat and impact treatment of the surface of titanium alloys which is accompanied by ultrahigh rates of heating (up to temperatures exceeding the melting point) and cooling provide a so-called self-quenching effect associated with $\beta \rightarrow \alpha'$ transformation via the diffusionless martensitic mechanism that results in the formation of lamellar martensitic structure. Moreover, redistribution of alloying elements can occur leading to the homogenization of phase composition of surface layers or emergence of new metastable phases and compounds which cannot be obtained using traditional methods of heat treatment.

Compared with pulsed electron beam processing the continuous electron beam scanning treatment is capable to increase strength of 3D-printed parts with large surface area. Moreover, high efficiency of continuous electron beam treatment is achieved through the control of both the electron beam power and the speed of the sample movement during the treatment. The purpose of this work is to compare the applicability of scanning electron beam treatment for modification of the surface morphology and microstructure of Ti-6Al-4V titanium cast alloy and Ti-6Al-4V parts manufactured by electron beam melting (EBM) process.

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2. Experimental details

The investigated materials were the as-received titanium Ti-6Al-4V alloy produced by casting and Ti-6Al-4V parts built by EBM of commercially available welding wire.

EBM was performed using an electron beam welding machine 6E400 (Teta, Russia) operating in a vacuum below 1.3×10^{-3} Pa at an acceleration voltage of 30 kV. The movement of the 150×150 mm base plate along X, Y and Z axes was provided by a 3-axis computer-controlled positioning system. The distance between the electron beam gun and the base plate (working distance) was 630 mm. At the beginning of a build process the titanium base plate was heated up to 900°C. Ti-6Al-4V welding wire 1.6 mm in diameter was melted with a plasma power source onto the plate surface to build up a part. Beam currents were ranged from 24 to 17 mA. The speed of platform movement along the XY and Z-directions was equal to 5 and 1 mm/s correspondingly.

The electron beam welding machine was also used for the continuous scanning electron beam treatment of Ti-6Al-4V cast alloy and Ti-6Al-4V parts manufactured by the EBM process. A sawtooth signal with a frequency of 100 Hz was used to turn the electron beam into a line of 27 mm length. The accelerating voltage and beam current were 30 kV and 60 mA, respectively. The both types of samples were processed, being moved with a speed of 20 mm/s with respect to the deflected electron beam**.** The focused electron beam with a spot of 0.5 mm in diameter treated the sample surface line by line. The electron gun power and the sample movement speed were chosen to provide an energy density of 450 J/cm².

The surface morphology of the titanium samples was studied using a Solver HV atomic force microscope (AFM) and a New View 6200 3D optical profiler. A Carl Zeiss Axiovert 40 MAT optical microscope, and a LEO EVO 50 scanning electron microscope (SEM) equipped with EBSD and EDS detectors were employed for microstructural characterization of the samples in the plan-view and cross-section geometries. Samples for metallographic study were cut both along and perpendicular to the build direction using electrical discharge machining. The surface roughness of the samples under study was measured by a profilometer Alpha-Step IQ (KLA-Tencor).

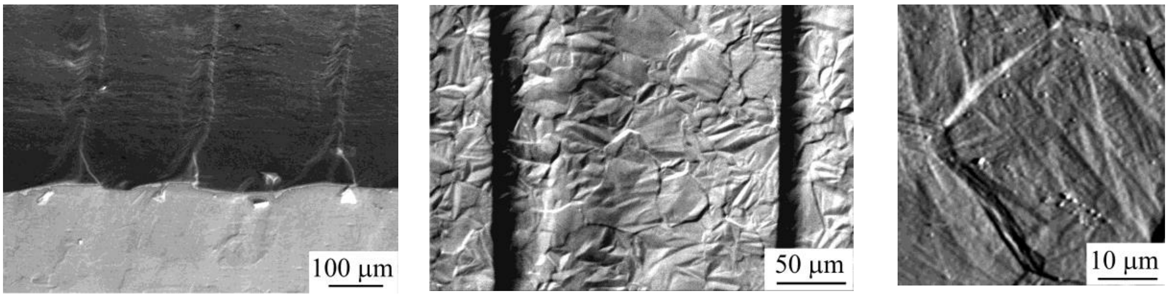
The Vickers microhardness of the modified surface layer was evaluated under 50 g load for 10 seconds.

3. Results and discussion

Ti-6Al-4V titanium alloy produced by casting is composed of equiaxed α-grains with an average grain size of 2 μm and of 500 nm β-grains located at α-grain boundaries or triple junctions. During the continuous scanning electron beam treatment high energy electrons are focused to a narrow spot and deflected so as to form a deep and narrow melted zone on the sample surface. The chosen processing parameters are used to cover the entire surface by multiple overlapping tracks. As a result, grooved surface topography caused by the pile up of molten metal near the edge of the melted zone is observed (figure 1a). The quantitative analysis carried out by optical profilometry reveals that the pile-ups reach a height of about 7 μm, while the average groove width is equal to 20 μm. Detailed SEM- and AFM imaging revealed α-grains with a grain size of about 45 μm within the melted surface layer (figure 1b,c). Such α-grains are characterized by the rippled topography due to rapid solidification of the melted surface layer into β-grains followed by the solid state β→α' martensitic transformation [5]. The XRD study confirms that such treatment doesn't change the volume fraction of α and β phases in the melted surface layer of Ti-6Al-4V titanium cast alloy. Cross-section EBSD analysis of the samples under study showed that the modified surface layer consists of the 30 μm thick melted zone and the 50 μm thick underlying heat-affected zone. The microhardness of the uppermost surface layer of Ti-6Al-4V titanium cast alloy increases from 3600 to 6450 MPa after scanning electron beam treatment [6].

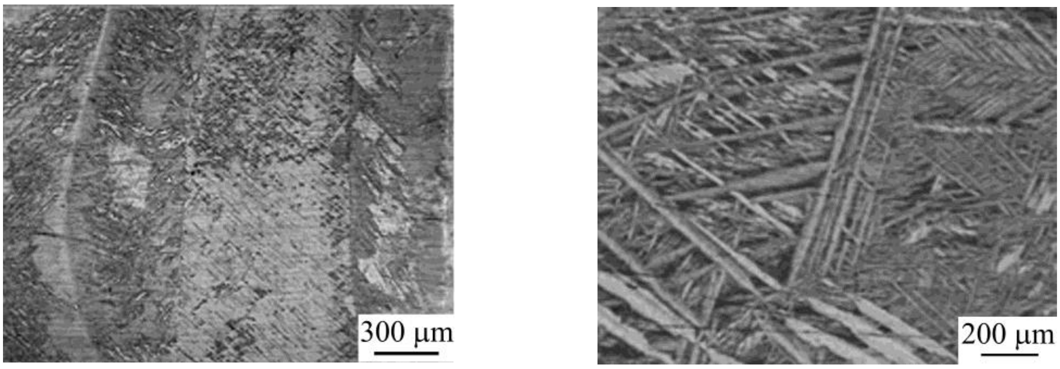
During the EBM process a titanium wire is fed into the path of an electron beam resulting to the banding structure that originates from overlapping thermal fields from sequential pool passes. Ti-6Al-4V parts in the as-built state are characterized by columnar prior β grains growing throughout the deposited layers (figure 2a). The lateral size of the columnar β grains varies between 500 μm and

1 mm. It is clear from figure 2b, that the grains consist of the acicular α' martensitic phase due to high cooling rates of deposited layers (~10^4 K/s) [7].



(a) (b) (c)

Figure 1. SEM-(a, b) and AFM images (c) of the surface of the Ti-6Al-4V cast alloy subjected to scanning electron beam treatment.

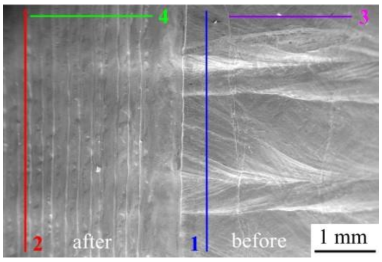


(a) (b)

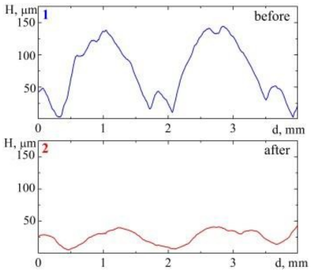
Figure 2. Cross-section view of columnar prior β grains (a) and microstructure of the as-built Ti-6Al-4V parts (b).

The scanning electron beam treatment was effectively used to smooth the rough surface of the EBM manufactured Ti-6Al-4V parts as well as to decompose the martensitic structure into a lamellar structure**.** As seen from figure 3a, the as-built Ti-6Al-4V parts are characterised by the grooved surface topography, whereas the surface of the parts subjected to scanning electron beam post- treatment becomes more smoother. The evidence of the latter is a less rough profile directed parallel to the build direction (figure 3b). At the same time, however, smaller grooves perpendicular to the build direction appear. For the as-build parts the height difference between the peak and valley of the profiles obtained in vertical and horizontal directions is equal to 150 and 15 µm (figure 3b, profile 1 and figure 3c, profile 3). After scanning electron beam treatment, the height difference of the profiles in vertical and horizontal directions are 50 and 30 µm, respectively (figure 3b, profile 2 and figure 3c, profile 4).

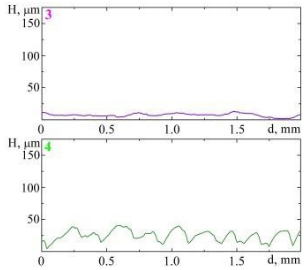
The EBSD analysis of the lateral face of the EBM fabricated Ti-6Al-4V parts subjected to scanning electron beam treatment reveals that the thickness of their modified surface layer is equal to 150 µm. Although clear grain structure was not found in the modified surface layer, it is evident from figure 3c that α' martensitic plates become thinner. As in the case of the Ti-6Al-4V cast alloy, scanning electron beam treatment increases the surface microhardness of the Ti-6Al-4V parts from 2900 to 4000 MPa.



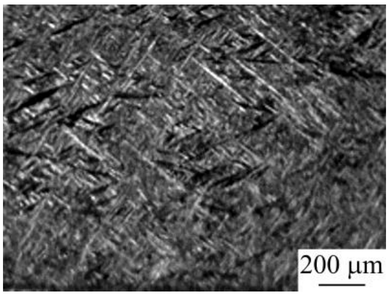
(a)



(b)



(c)



(d)

Figure 3. SEM-images (a, d) and corresponding profiles (b, c) of Ti-6Al-4V parts built by EBM process before (profiles 1, 3) and after scanning electron beam treatment (profiles 2, 4).

4. Conclusion

This paper summarises the results obtained when studying the effect of scanning electron beam treatment on the surface morphology and microstructure of titanium Ti-6Al-4V alloy produced by casting and EBM processes. It is found that the entire surface of the samples under study is covered by multiple overlapping tracks formed by melt bath movement during irradiation with an energy density of 450 J/cm². Despite the fact that scanning electron beam treatment results in the grooved surface topography, the melted surface layer of the EBM printed parts becomes more smoother in comparison with the as-build parts. Microstructure of Ti-6Al-4V titanium cast alloy and EBM printed Ti-6Al-4V parts after scanning electron beam treatment is composed of α'-martensite, and the α plates in the modified surface layer of 3D printed parts are larger than those in the cast alloy.

Scanning electron beam treatment increases the microhardness of both Ti-6Al-4V titanium cast alloy and Ti-6Al-4V parts manufactured by EBM process by 1.8 and 1.4 times, respectively.

Acknowledgments

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