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VIII ВСЕРОССИЙСКАЯ НАУЧНО-ПРАКТИЧЕСКАЯ КОНФЕРЕНЦИЯ С МЕЖДУНАРОДНЫМ УЧАСТИЕМ, ПОСВЯЩЕННАЯ 50-ЛЕТИЮ ОСНОВАНИЯ ИНСТИТУТА ХИМИИ НЕФТИ

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SURFACE MODIFICATION OF SELECTIVE LASER MELTED Ti-6Al-4V PARTS BY ULTRASONIC IMPACT TREATMENT AND ELECTRON BEAM IRRADIATION

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Abstract. Changes of the surface roughness, microstructure, phase composition and microhardness of selective laser melting Ti-6Al-4V samples during electron beam irradiation and ultrasonic impact treatment were investigated by contact profilometry, optical microscopy, X-ray analysis, and hardness measurement. It was shown that electron beam irradiation and ultrasonic impact treatment of the selective laser melted Ti-6Al-4V samples smooth their surface. Significant refinement of the microstructure and TiO nanoparticles formation under ultrasonic impact treatment occur causing the increased surface microhardness. Electron beam irradiation intern leads to a more significant increase in both the microhardness and thickness of the melted surface layer due to martensitic transformation.

Introduction

In recent years, additive manufacturing of Ti–6Al–4V parts has made significant progress, especially with respect to process optimization and property characterization. Selective laser melting (SLM) is one of the promising technologies that have been attracting increasing attention in aerospace and biomedical fields due to their advantages of producing prototypes or finalized parts rapidly and cost-effectively, whilst providing accurate control over both internal architectures and complex-shapes [1,2]. In SLM, consolidation of metal powder is achieved by melting and solidifying a small volume of material in a track-by-track and layer-by-layer fashion using a high-intensity laser. On repeating the single track deposit with a well-defined overlap (hatch spacing), a layer of a cross-section is produced. Upon repeating this layer-by-layer deposition, an entire part is constructed [3]. However, due to insufficient energy on the melt pool, edge only partial melted powder particles occur. Additionally, the top and side surfaces are characterized by the stair step effect as a result of the layer wise character of the SLM process. Surface roughness is critical for many applications, so parts fabricated by the SLM method require machining before being put in use.

Nowadays, increasing interest is given to mechanical grinding and polishing [4], ball burnishing [5], shot peening [6], ultrasonic impact treatment [7], and other mechanical post-processing technologies that allow not only smoothening of the rough surface finish of as-fabricated parts, but also an increase of their hardness, strength, wear resistance, and fatigue life. Besides, the pulsed electron beam irradiation can be effectively used as thermal post-processing techniques of 3D–printed titanium components [8]. In the present work, ultrasonic impact treatment based on plastic deformation of the surface and electron beam irradiation causing the melting of the surface layer and its rapid crystallization are considered as post-processing methods.

Experimental details

The powder of Ti-6Al-4V alloy manufactured by AP & C, a Canada-based company, was used as an initial material for 3D printing of samples. Average particle size is ~ 30 μm. SLM samples were produced on the EOSINT M280 machine (EOS Electro Optical Systems, Munich, Germany), equipped with an CO laser. Cuboid blanks with the dimensions of 10×10 mm and height of 70 mm were vertically fabricated in an argon atmosphere on a 10-mm thick titanium plate. Square samples of 10x10x1 mm designed for structural studies and microhardness measurements were cut out from each of the blanks by electro-discharge machining.

Ultrasonic impact treatment of the SLM TI-6AL-4V samples was carried out in air with natural air cooling using an IL4 ultrasonic generator. The ultrasonic generator had an output power of 2000 W and a frequency of 25 kHz. The impact load of the striker was 150 N. The speed of the striker along the X and Y-axes was 1.5 and 3 mm/s, respectively.

The low energy high current pulsed electron beam irradiation of the SLM TI-6AL-4V samples was carried out using a SOLO (IHCE SB RAS, Tomsk) electron-beam plant by 6 consecutive pulses 120 µs in length. The beam energy density (fluence) was equal to W=60 J/cm^2, the energy of electrons was 17 KeV and the pulse frequency was 0.3 s^{-1}. The irradiation was performed in Ar atmosphere at a residual pressure of 0.02 Pa.

The surface morphology of the as-fabricated and post treated SLM samples was studied, using a Leo EVO scanning electron microscope (SEM) and a New View 6200 3D optical profiler. Metallographic studies in the longitudinal and transverse sections of etched 3D-printed samples were performed using Zeiss Axiovert 40 MAT. The microhardness was measured at the lateral surface of Ti–6Al–4V alloy samples using the 50 g load for 10 s. The first measurement of microhardness was made at a distance of 10 µm from the top surface. Each microhardness point was obtained by doing parallel measurements at the same distance on the lateral surface and calculating the average value. The distance between any two neighboring indentations was more than 10 µm.

Results and discussion

Surface profile of the as-fabricated SLM sample revealed an irregular surface composed of peaks and valleys (Fig.1,a, curve 1). As can be seen in Fig.1,b, SLM samples contain partly melted powder particles adhered to the surface. The size of these partially sintered particles (~30 µm average) is comparable to the powder particles used for the fabrication of the part. The roughness analysis reveals that the root mean square roughness (Rq) of the as-fabricated samples, determined by contact profilometry, is 20 µm.

During electron beam irradiation rapid heating, melting, and crystallization in a thin melted layer of the SLM Ti-6Al-4V samples occur causing the surface smoothing and formation of grain structure on it (Fig.1,a, curve 2 and Fig.1,c,d). The lateral size of the surface grains is 250 µm. The root mean square roughness of the electron-beam irradiated samples is Rq=2.51 µm.

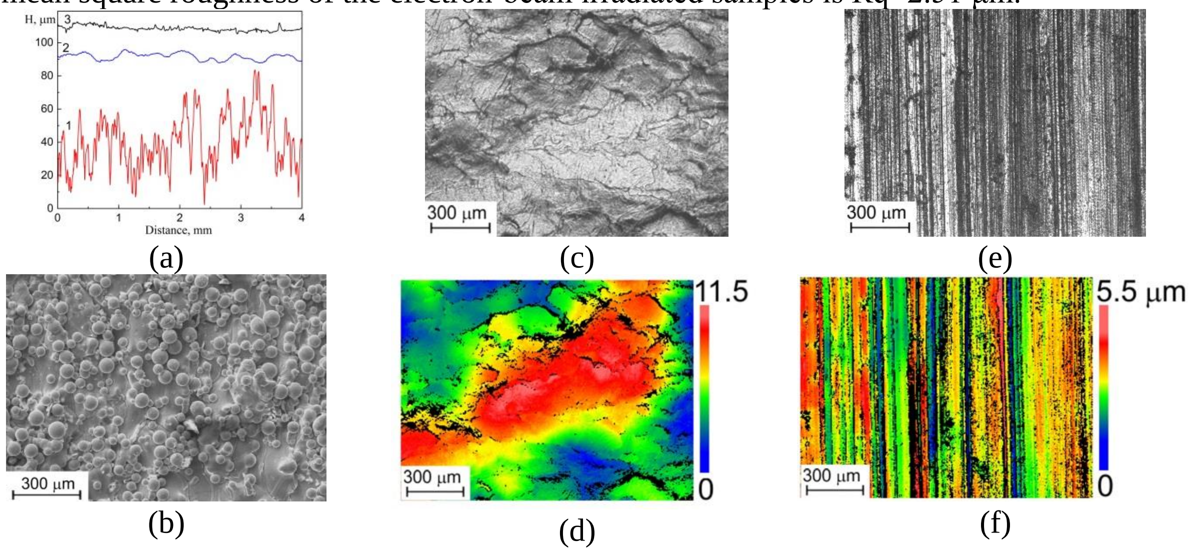


FIG. 1. Surface profiles (a), SEM-mages (b) and optical images of the surface ((c-f)) of as-fabricated (b), electron beam irradiated (c,d) and ultrasonically treated SLM sample (t, f). (a): 1-as-fabricated, 2-electron beam irradiated and 3- ultrasonically treated SLM Ti-6Al-4V samples

During ultrasonic impact treatment the impact of a striker oscillating at an ultrasonic frequency caused the formation of periodic hills, 150 µm wide and 3 µm high, along the entire surface of the SLM samples (Fig. 1,a, curve 3 and Fig. 1,e,f). These hills are formed as a result of plastic displacement of the processed material along the edges of the metal striker moving across the surface of the sample. The root mean square roughness of the ultrasonically treated samples decreases to Rq=0.48 µm.

X-ray analysis of SLM Ti-6Al-4V samples reveals peaks of hpc α phase with lattice parameters a = 2.9233, c = 4.6633 Å. There are no peaks of β phase on the diffraction pattern (Fig. 2, curve 1). In addition, the SLM samples are characterized by the presence of high internal tensile macrostresses, reaching 2.9 GPa. The electron beam irradiation of the SLM sample causes a change in the intensity of the α phase peaks, which indicates the occurrence of recrystallization processes in the melted surface layer. Along with a change in the intensity, broadening of the α phase peaks is observed which can be caused both by strong distortion and by α′ phase formation in the melted surface layer (Fig.2, curves 1 and 2). Internal tensile macrostresses reduce to 150 MPa under electron beam irradiation. After ultrasonic impact treatment (Fig.2, curve 3) the intensity of the α-phase peaks is considerably lower than in the as-fabricated Ti-6Al-4V sample, and significant broadening of the peaks is also observed. It is indicative of high residual compressive stresses (1.5 GPa) and significant refinement of crystallites. Besides, redistribution of individual α-phase peak intensities appears to take place along with formation of the preferred crystallographic orientation (002). β-phase peaks are also not observed, while peaks corresponding to titanium oxide TiO appear on X-ray patterns of samples subjected to ultrasonic impact treatment (Fig.2, curve 3).

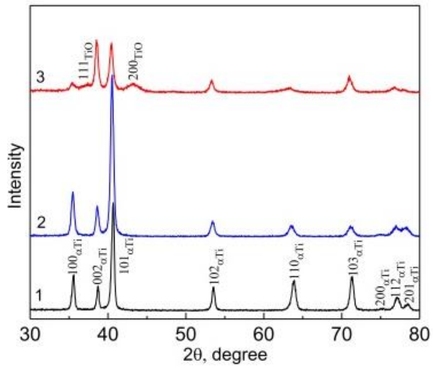
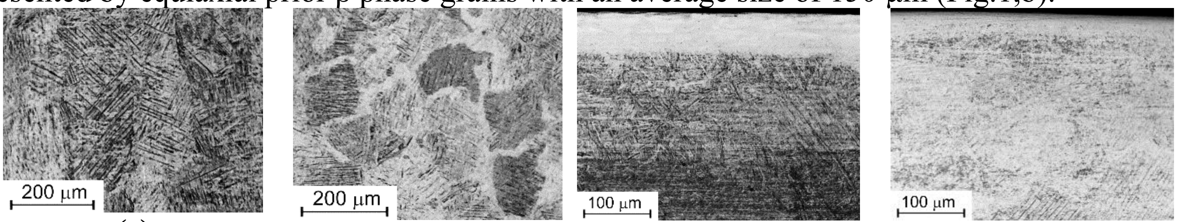


FIGURE 2. X-ray diffraction patterns of as-fabricated (1), electron beam irradiated (2) and ultrasonically treated SLM Ti-6Al-4V samples (3)

The microstructure of the as-fabricated Ti-6Al-4V sample was studied both in orientation parallel to the direction of sample growth (longitudinal-section) and in orientation parallel to the substrate (cross-section). It was established that with layer-by-layer growth of the studied samples high temperature gradients form within the samples, as a result the microstructure of the SLM samples in the longitudinal and transverse sections is markedly different. As can be seen in Fig. 3,a, in the plane parallel to the sample growth direction the macrostructure is represented by columnar prior β phase grains with a high degree of anisotropy. The width of the columnar grains varies from 100 to 200 μm, and their length reaches 600 μm. The microstructure in the cross-section of SLM samples is represented by equiaxial prior β phase grains with an average size of 150 μm (Fig.1,b).



(a) (b) (c) (d)

FIG. 3. Cross-section optical images of as-fabricated (a), electron beam irradiated (b) and ultrasonically treated SLM Ti-6Al-4V samples (c) with subsequent etching

Electron beam irradiation and ultrasonic impact treatment were performed along longitudinal sections and metallographic studies were done on transverse sections of the SLM samples. Electron beam irradiation of as-fabricated SLM samples resulted in substantial structure modification of their surface layer caused by its melting followed by rapid crystallization. The cross-section analysis of the samples by optical microscopy showed that the modified surface layer has a multilayer structure (Fig.3,c). The homogenous melted layer having a brighter contrast is formed at the top surface. The heat-affected zone is located below this layer. The thickness of the melted surface layer and the heat-affected zone are 60 and 130 μm, respectively.

Cross-sectional optical images of ultrasonic treated samples reveal significant grain refinement in the thin surface layer which manifest itself in a white (non-etched) continuous layer on the metallographic images (Fig.3,d). The depth of the modified surface layer is 30 μm.

Electron beam irradiation of SLM samples leads to a twofold increase in the microhardness (10 GPa) of their surface layers (Fig.4, curves 1 and 2). Three segments of the microhardness vs. distance from surface plots can be distinguished: (i) the one with constant high hardness, which well agrees with the thickness of the melted surface layer; (ii) the one with gradient descending hardness that corresponds to the heat affected zone; and (iii) the one with the hardness typical for as-fabricated Ti–6Al–4V alloy (Fig.4, curve 2). Grain refinement and formation of slip bands and twins in surface layer of the SLM samples subjected to ultrasonic impact treatment causes an increase in their surface microhardness to 8.5 GPa (Fig.4, curve 3). The depth of the hardened surface layer does not exceed 30 μm.

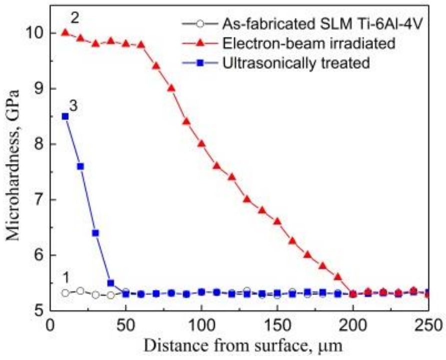


FIG. 4. Microhardness of as-fabricated (1), electron-beam irradiated (2)
and ultrasonically treated SLM Ti-6Al-4V samples (3) vs. distance from surface

Summary

It was shown that electron beam irradiation and ultrasonic impact treatment of the SLM Ti-6Al-4V samples lead to a significant reduction of the surface roughness. The roughness analysis reveals that the root mean square roughness of the as-fabricated samples, determined by contact profilometry, is 20 μm. Intensive plastic deformation of SLM Ti-6Al-4V samples under ultrasonic impact treatment leads to significant grain refinement and reduction of the surface roughness to Rq=0.48 μm. Under electron beam irradiation as a result of rapid heating, melting, and crystallization grain size is rise to 250 μm. The different growth rates of prior β grains with different crystallographic orientations cause the orange-pill surface effect and root mean square roughness of irradiated sample reduce to Rq=2.51 μm.

Moreover, electron beam irradiation and ultrasonic impact treatment are effective hardness enhancement methods. Microstructure refinement and formation of titanium oxide TiO in a surface layer of SLM Ti-6Al-4V samples subjected to ultrasonic impact treatment causes increase in microhardness from 5.3 to 8.5 GPa. The depth of hardened surface layer is 30 μm. The depth of the hardened surface layer formed under electron beam irradiation is more pronounced (200 μm) and the maximum hardness reaches 10 GPa. The latter can be associated with α' phase formation in the melted surface layer as a result of rapid cooling.

Acknowledgments

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