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MICROSTRUCTURE AND MECHANICAL TENSILE PROPERTIES OF A VT6 ALLOY MANUFACTURED BY SELECTIVE LASER MELTING

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The microstructure and tensile properties of a material manufactured from the VT6 titanium alloy by the method of selective laser melting (SLM) are investigated. In the initial state, the microstructure of the SLM-material consists of columnar β-grains elongated in the direction of heat sink, which were transformed during cooling into the acicular martensite α'-phase. A heat treatment, including two-stage annealing at 900 and 700°C, transfers the microstructure into equilibrium, two-phase state, with the elongation of β-grains being retained. Mechanical tensile tests were performed in the direction normal to the layer packing formed during SLM. It is found that strength properties of the workpiece manufactured by the SLM process are similar to those of the VT6 alloy manufactured by conventional casting, while its room-temperature ductility is noticeably higher. Deformation-relief studies of the specimen surface demonstrated that the layers formed during SLM affect neither the development of deformation nor fracture of the material.

Keywords: titanium alloys, selective laser melting, microstructure, mechanical properties.

INTRODUCTION

The method of selective laser melting (SLM) or layer-by-layer laser melting belongs to laser additive manufacturing processes used for making three-dimensional components without any intermediate mechanical treatment operations or hot die forging [1–4]. The essence of the method is in the use of a scanning laser beam for melting the powder and layer-by-layer melting of a workpiece/component of a predesigned shape by gradual addition of the material. An application of the SLM process reduces the total production time and cost of the workpiece/component in the case of small-batch production. Moreover, SLM exhibits such important advantages as:

– manufacturing geometrically complex parts, including those with thin walls, which is hard to achieve by casting, especially for the alloys with poor casting characteristics;

– manufacturing parts of complex chemical compositions, including those with a gradient structure and unique service properties;

– absence of casting stresses in the resulting component;

– absence of porosity and surface contamination of the component material, given properly selected technological parameters, in contrast to powder metallurgy processes, which is especially valuable for the materials with high reaction capacity;

– material saving, which is critical, given its high cost, but is unachievable under conditions of conventional production based on mechanical machining of components.

The SLM method has been tested for manufacturing components/parts both from classical aluminum-, nickel-, steel-, titanium-base alloys and, within recent time, from intermetallic alloys [5] and composites [6]. It has been shown

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in [7- 9] that materials produced from a titanium alloy Ti – 6Al – 4V by the SLM method possess properties close to those exhibited by the alloy manufactured via conventional casting, though a few authors report lower mechanical properties, in particular poorer fatigue strength [10]. It has been found that the properties of the SLM material depend on the melting parameters (scanning strategies, beam power, laser beam velocity, etc.), which determine the material structure, texture and porosity. Another important process is heat treatment of the material manufactured by the SLM method. In particular, it has been shown for Ti – 6Al – 4V that hot isostatic pressing [7] and annealing within the range of (α+β)-phase region followed by furnace cooling exert, in general, a positive effect on its mechanical properties [8]. As concerns the SLM-workpieces/components, the effect of the layers (formed using any scanning strategy) on the deformation and fracture mechanism and mechanical properties is still poorly studied.

The purpose of this work is to investigate the microstructure of a rod manufactured by SLM from a VT6 alloy, including that after heat treatment and the effect of the layers formed during SLM on the evolution of deformation and tensile properties.

MATERIAL AND EXPERIMENTAL PROCEDURE

The specimen under study was a rod manufactured by the SLM process from a VT6 titanium alloy. The rod measured ∅ 11 × 100 mm. The material layers added in the course of SLM process were perpendicular to the rod axis.

Examination of the microstructure was performed in the OlympusGX51 optical microscope (OM) and Tescam Mira 3 scanning electron microscope (SEM) in the modes of backscattered electrons (BSE) or secondary electrons (SE). The energy-dispersive X-ray spectral analysis was performed from the butt-ends of the rod at different distances from the rod axis using CuK_α-radiation.

Heat treatment of the specimens was performed in the ATS furnaces with kanthal heaters. The heat treatment included annealing at $T = 900$°C (τ = 1 h) followed by furnace cooling and a subsequent annealing at $T = 700$°C (τ = 2 h) followed by cooling in air.

Mechanical tensile tests of the rod in a heat-treated state were performed in air at the temperatures $T = 20$ and 400°C at the initial strain rate $\varepsilon' = 8.3\cdot10^{-4}$ s^{-1}. The flat specimens with a gage section of 10 × 3 × 1.5 mm were used for tensile testing. Four specimens per point were tested at room temperature and two specimens per point – at elevated temperature.

The deformation relief was investigated on the surface of pre-polished specimens after tensile tests at room temperature.

RESULTS AND DISCUSSION

The microstructure of the rod in the initial state and after heat treatment is presented in Fig. 1. In the initial microstructure, there are distinctive horizontal layers about 300 μm thick, which were formed during SLM processing via gradual addition of the material (Fig. 1*a*). Between the layers, there are dark bands (interlayer boundaries) measuring about 50 μm. Different etching patterns suggest that the chemical compositions of the intra- and interlayer space were different.

The rod has a martensitic structure with grains elongated in the direction perpendicular to the layer packing (Fig. 1*a*). These are likely to be columnar β-grains elongated in the direction of heat sink in the course of solidification under conditions of fast cooling. Note that the columnar β-grains were also reported in the material manufactured by the SLM method from a Ti – 6Al – 4V alloy in [3, 7–10]. Heat treatment results in disappearance of the boundaries between horizontal layers and gives rise to formation of the basket-pattern structure characteristic of (α+β)-titanium alloys (Fig. 1b). It is evident that elongation of the transformed β-grains is retained. The initial material contained pores measuring up to 100 μm.

In the initial state after SLM, the microstructure largely consists of the martensitic α′-phase. This is suggested by the broadening of α-Ti peaks and by the virtual absence of β-Ti peaks in the diffraction pattern corresponding to the initial state (Fig. 2*a*), which is indicative of oversaturation of the solid α′-solution. After heat treatment, broadening of

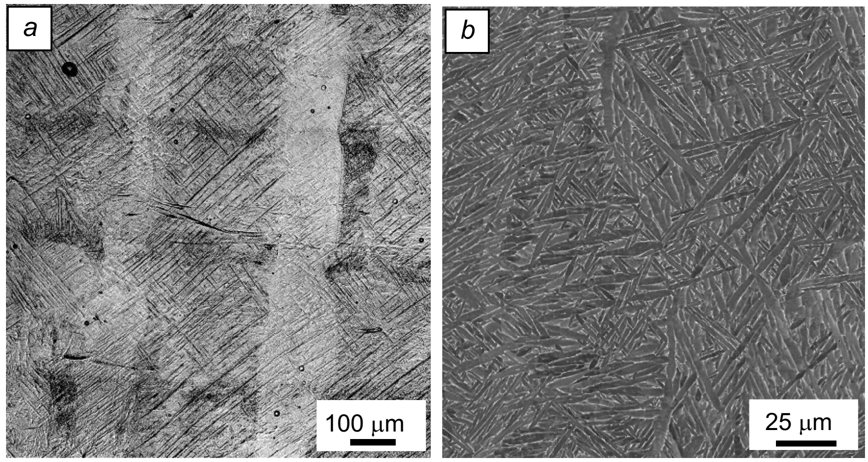

Fig. 1. Microstructure of the axial section of the rod manufactured by SLM from a VT6 alloy: in the initial state (OM) (*a*) and after heat treatment (SEM) (*b*). The layers are horizontal (*a*), β-grains are elongated in the direction parallel to the rod axis (*a*, *b*).

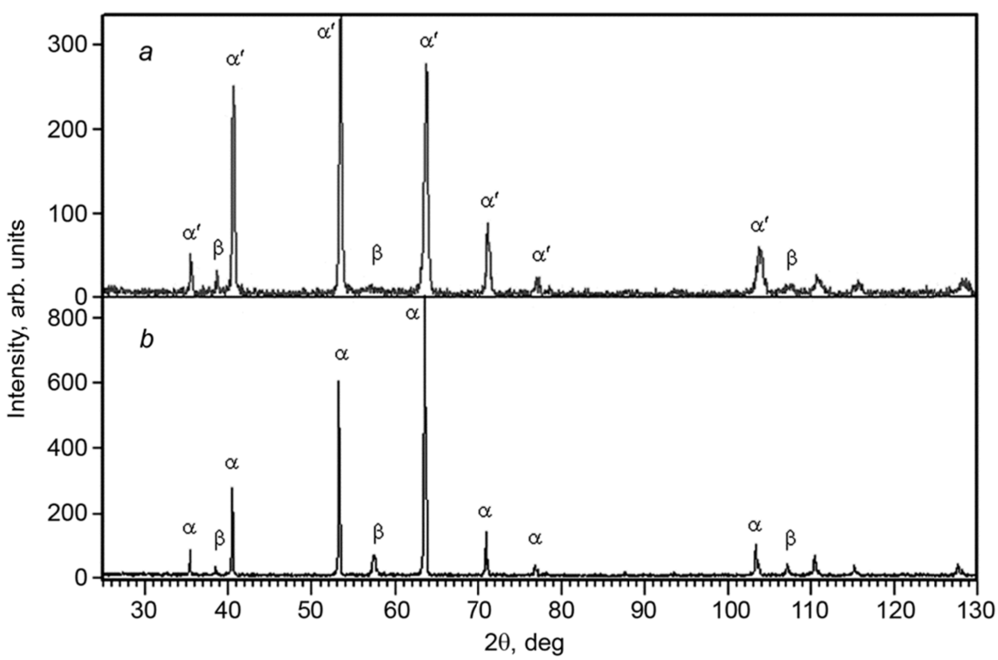

Fig. 2. Diffraction patterns obtained from a rod manufactured by SLM from a VT6 alloy: initial state (*a*) and after heat treatment (*b*).

α′-peaks disappears and distinctive peaks corresponding to the β-Ti phase are evident in the pattern (Fig. 2*b*). Thus, the heat treatment including annealing at T = 900°C, furnace cooling and a second annealing at T = 700°C, transfers the microstructure into an equilibrium two-phase state.

Table 1 lists the data on local measurements of the chemical composition using an energy dispersive X-ray analysis. It is evident that the SLM process ensures high chemical homogeneity in the material bulk.

Table 2 presents the tensile properties of the specimens, which were cut from the annealed rod manufactured by the SLM method and from the annealed VT6 alloy manufactured by conventional casting. Their comparison

TABLE 1. EDX Data from the Rod in the Initial State Manufactured by the SLM Method from a VT6 Alloy

Butt end of the rod	Content of elements, wt.%		
	Al	Ti	V
Conventional top	6.40 ± 0.1	89.93 ± 1	3.67 ± 0.12
Conventional bottom	6.26 ± 0.1	90.10 ± 1	3.65 ± 0.12

TABLE 2. Mechanical Properties of a Heat-Treated Rod Manufactured by SLM from a VT6 Alloy as Compared to those a Heat-Treated VT6 Alloy Manufactured by Conventional Casting [11]

Method	20°C			400°C		
	δ,%	$\sigma_{0.2}$, MPa	σ_U, MPa	δ,%	$\sigma_{0.2}$, MPa	σ_U, MPa
SLM + annealing T = 900°C (1 h) + 700°C (2 h)	15	855	988	15	414	644
Casting + annealing T = 955°C (1 h) + 620°C (2 h)	5–8	855–900	935–970	–	–	–

demonstrates that the strength of the SLM-material and the conventional alloy is nearly the same, while its ductility is considerably higher. The latter could be ascribed to the refined microstructure produced by SLM as a result of fast cooling. In the case of conventional casting, the rate of workpiece cooling is much lower, which gives rise to a fast growth of β-grains.

An examination of the surface deformation relief demonstrated that the deformation is more extensively developed within the β-phase, which is softer than the α-phase. This gives rise to deformation incompatibility between the α- and β-phases and to nucleation of cracks between them (Fig. 3*a*, *b*). The fracture is of predominantly ductile character (Fig. 3*c*). No effect of the layers formed during SLM on the evolution of deformation and fracture is detected.

Thus, the SLM process ensures manufacturing of a chemically homogeneous rod with a structure mainly consisting of the martensitic α′-phase. Heat treatment consisting of two stages of annealing at the temperatures of the (α+β)-phase region transfers the material into a thermodynamically equilibrium two-phase state. The investigation of the tensile properties and the surface deformation relief of the specimens deformed at room temperature shows that the deformation mechanisms and mechanical behavior of the material manufactured by SLM and subjected to subsequent heat treatment are similar to those of the heat treated VT6 alloy manufactured by conventional casting. No effect of layers formed during SLM processing on the evolution of deformation and fracture is revealed, which suggests that the cohesive strength between the layers corresponds to that of the conventionally manufactured material.

SUMMARY

The microstructure and tensile properties of a material manufactured by the SLM process from the VT6 cast titanium alloy have been investigated. The presence of layers, measuring about 300 μm in thickness, formed during SLM has been revealed. It has been found that in the initial state the microstructure of the SLM material predominantly consists of the martensitic α′-phase, which after annealing is transformed into a two-phase (α+β)-state. Examination of the surface relief of the specimen deformed at room temperature did not reveal any effect of the layers on the evolution of deformation and fracture. It has been shown that deformation occurs more extensively in the β-phase, which gives rise to the incompatibility of deformation between the α- and β-phases and the nucleation of cracks between them. The tensile tests along the direction perpendicular to the layer packing formed during SLM have shown that the strength properties of the material produced by the SLM method are nearly the same as those of the VT6 alloy manufactured by conventional casting. Furthermore, the ductility of the SLM material has been found to be higher than that of the VT6 alloy manufactured by conventional casting, which can be ascribed to a refined microstructure formed during SLM as a result of fast cooling.

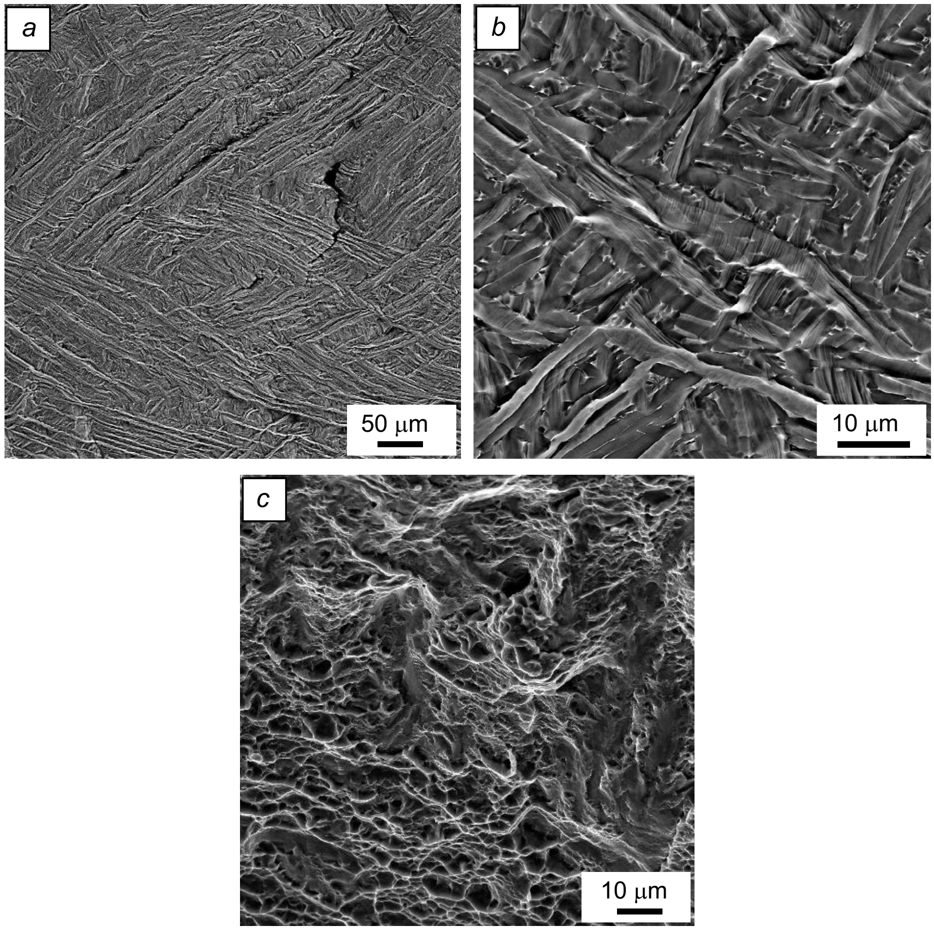

Fig. 3. Deformation relief on the surface of the specimen cut from the rod manufactured by SLM from the VT6 alloy under different magnifications (*a*, *b*) and the fracture surface of the tensile specimen at room temperature (*c*).

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