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Dependence of structure and properties of VT23 alloy on laser deposition parameters

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Abstract. The study analyzes the effect of laser power and velocity on the structural phase state and properties of complex-alloyed titanium alloy VT23 (Ti–Al–V–Mo–Cr–Fe) obtained by direct laser deposition. VT23 titanium alloy has a unique combination of strength, corrosion resistance, and biocompatibility, which makes it in demand in the aerospace and medical industries. However, traditional manufacturing methods (casting, stamping) often fail to provide the required accuracy and quality of complex parts. In this work, *X*-ray phase analysis and optical metallography revealed that the deposited samples consist of α- and β-phases (~20 % β-phase) with a typical "basket weave" structure. In macrostructure of the obtained samples, thermal bands and interlayer boundaries were recorded, the formation of which is associated with the peculiarities of crystallization process during direct laser deposition. The results of optical metallography showed that microstructure of the deposited material combines large columnar crystals in the overlap areas of two adjacent layers, as well as small equiaxed grains. Despite this distribution of structural components, the microhardness (~488 $HV_{0.2}$) remains homogeneous throughout the deposited samples in both the laser scanning and sample deposition directions. The results confirm that direct laser deposition can be used to produce VT23 titanium alloy parts with a controlled microstructure. Optimization of the process parameters of direct laser deposition minimizes the probability of defect formation and provides stable mechanical properties, which opens prospects for application of the technology in the production of critical parts.

Keywords: additive technologies, direct laser deposition, titanium alloys, complex alloys, microstructure, phase composition, mechanical properties

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Зависимость структуры и свойств сплава ВТ23 от параметров лазерного выращивания

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Аннотация. В данном исследовании проведен анализ влияния мощности лазера и скорости его перемещения на структурно-фазовое состояние и свойства сложнолегированного титанового сплава ВТ23, полученного методом прямого лазерного выращивания. Титановый сплав ВТ23 обладает уникальным сочетанием прочности, коррозионной стойкости и биосовместимости, что делает его востребованным в аэрокосмической и медицинской отраслях. Однако традиционные методы производства (литье, штамповка) часто не обеспечивают необходимой точности и качества сложных деталей. В данной работе методами рентгенофазового анализа и оптической металлографии установлено, что выращенные образцы состоят из α- и β-фаз (~20 % β-фазы) с характерной структурой «корзиночного плетения». В макроструктуре полученных образцов зафиксированы полосы термического воздействия и межслоевые границы, образование которых связано с особенностями процесса кристаллизации при прямом лазерном выращивании. Результаты оптической металлографии показали, что микроструктура выращенного материала сочетает в себе крупные столбчатые кристаллы в местах перекрытия двух соседних слоев, а также мелкие равноосные зерна. Несмотря на такое распределение структурных составляющих микротвердость (~488 $HV_{0,2}$) остается однородной по всему объему напечатанных образцов как в направлении сканирования лазера, так и в направлении выращивания образца. Результаты подтверждают, что прямое лазерное выращивание позволяет получать заготовки из титанового сплава ВТ23 с контролируемой микроструктурой. Оптимизация параметров процесса прямого лазерного выращивания минимизирует вероятность образования дефектов и обеспечивает стабильные механические свойства, что открывает перспективы для применения технологии в производстве ответственных деталей.

Ключевые слова: аддитивные технологии, прямое лазерное выращивание, титановые сплавы, сложные сплавы, микроструктура, фазовый состав, механические свойства

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Introduction

Titanium alloys are widely known for their exceptional combination of high strength-to-weight ratio, excellent corrosion resistance, and biocompatibility, which makes them indispensable in aerospace, biomedical, and high-performance engineering applications [1 – 6]. Among these alloys, VT23 (Ti–Al–V–Mo–Cr–Fe) is particularly valued for its superior thermal stability, creep resistance, and weldability – properties that are critically important for aerospace components such as airframe structures, engine parts, and rocket housings [2 – 3]. Moreover, its biocompatibility and mechanical compatibility with human bone have promoted its use in medical implants, including orthopedic and dental prostheses [4 – 6]. However, traditional manufacturing methods such as casting and stamping often face challenges associated with the high reactivity, low thermal conductivity, and significant deformation resistance of titanium alloys, which complicate the production of complex geometries free of defects [4].

Additive manufacturing (AM) has emerged as a transformative approach to overcoming these limitations, with direct laser deposition (DLD) – one of the most promising directed energy deposition (DED) technologies – attracting particular attention. DLD offers unprecedented advantages such as near-net-shape fabrication, minimal material waste, and the ability to produce complex geometries that are difficult or even impossible to achieve by conventional means. Unlike powder bed fusion technologies such as selective laser melting (SLM), DLD enables the fabrication of large-scale parts, in-situ alloying, and hybrid manufacturing (e.g., repair or coating of existing components). However, the unique thermal cycles and rapid solidification inherent to DLD can lead to microstructural heterogeneity, residual stresses, and anisotropic mechanical properties that must be carefully managed to ensure optimal performance [4 – 10].

A critical issue in DLD of titanium alloys is the formation of large columnar grains and strong crystallographic textures along the build direction, which can adversely affect ductility and fatigue strength [4 – 15]. Furthermore, improper selection of process parameters may result in process-induced defects such as porosity, unmelted particles, and thermal cracking. Recent studies on similar titanium alloys (e.g., Ti–6Al–4V and TA15) produced by DLD have shown that laser power, scanning velocity, hatch spacing, and layer thickness have a pronounce [4 – 7; 9 – 10]. For instance, excessive energy input may cause porosity formation, while insufficient energy leads to lack of fusion. In addition, high cooling rates typical of DLD often promote the formation of acicular α′-martensite, which increases strength but reduces ductility compared with conventional α + β microstructures [4 – 7].

Considering these issues, the main objective of the present study is to systematically investigate the effect of direct laser deposition process parameters – including laser power, scanning velocity, and hatch spacing – on the microstructural evolution, phase composition, and mechanical properties of the VT23 alloy. By correlating the process–structure–property relationship, this study aims to establish optimized DLD parameters that minimize defects while achieving a balanced combination of strength and ductility.

Materials and methods

In this work, VT23 titanium alloy samples were fabricated by direct laser deposition (DLD). The chemical composition of the alloy is presented in the Table.

Wall samples measuring 50×90×90 mm were fabricated by DLD method on a VT1-0 titanium alloy substrate. Deposition parameters were as follows: laser power of 1000 and 1100 W; scanning velocity of 1 m/min; and overlap between adjacent tracks equal to 0.7 of the track width.

Favorable process parameters were first screened on single tracks and then on monolayers.

The quality of a single track was evaluated according to the following criteria:

– track shape factor f ($f = h/L$, where h is the bead height above the substrate; L is the single track width, Fig. 1, *a*)) should be within the range [0.20; 0.33];

Chemical composition of VT23 powder

Химический состав порошка ВТ23

Mass fraction, wt. %									
Ti	Al	V	Mo	Cr	Fe	O	H	N	C
Base	4.8	4.5	2.6	1.2	0.4	0.12	0.004	0.018	0.03

– penetration coefficient d should be within the range [0.1; 0.4]

$$d = \frac{S_p}{S_p + S_h},$$

where S_p and S_h are the bead areas below and above the substrate surface, respectively;

– track width L should be within 1.7 – 3.0 mm for a laser spot diameter of 1.8 mm;

– base angle of the bead θ should be less than 90° [11 – 17].

Another important quality criterion was the absence of cracks.

The parameters of the monolayers had to satisfy the following conditions:

– height variation of the monolayer (h_2/h_1) did not exceed 30 % of its maximum height;

– penetration depth was less than two-thirds of the layer height (Fig. 1, *b*) [12; 17].

To study the structure, two sections were examined – along the deposition direction (*XZ*), and – along the laser scanning direction (*XY*) (Fig. 2).

Metallographic studies were performed on micro-sections prepared using standard procedures: grinding on abrasive paper and polishing with diamond suspensions (down to 1 μm). Etching to reveal structural features was carried out in a solution containing 3 mL HF, 15 mL HNO_3, and 82 mL H_2O.

Structural examinations were conducted using an Olympus GX-51 inverted optical microscope at magnifications ranging from 50 to 500$^{\times}$.

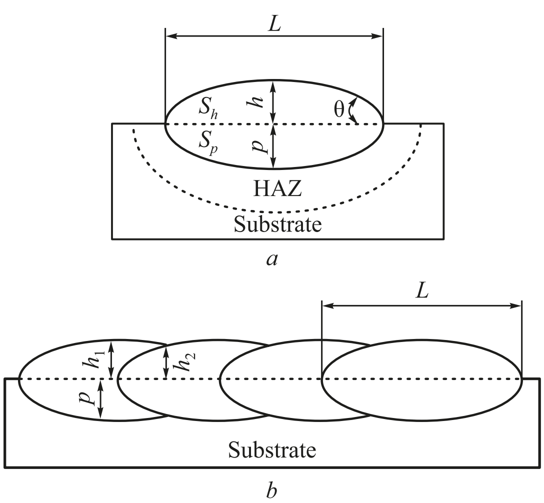

Fig. 1. Scheme of shapes:
a – single track; *b* – monolayer

Рис. 1. Схема форм:
a – единичный трек; *b* – монослой

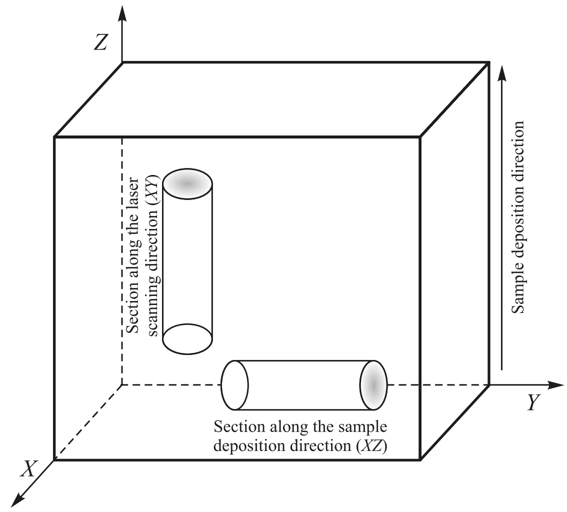

Fig. 2. Sample cutting scheme

Рис. 2. Схема вырезки образцов

For the analysis of the phase composition, samples were prepared for *X*-ray diffraction analysis. The preparation included grinding and electrolytic polishing using a Struers LectroPol-5 unit in A2 electrolyte (78 mL $HClO_4$, 90 mL distilled water, 730 mL C_2H_6O, 100 mL $C_6H_{14}O_2$) for 15 min at 10 V.

X-ray diffraction patterns were obtained on a Bruker D8 Advance diffractometer with Bragg–Brentano focusing geometry, using CuK_α radiation over a 2θ range of 30–100° with a step size Δ2θ = 0.07° and an exposure time of 2 s per point. The tube voltage and current were 40 kV and 35 mA, respectively. A semiconductor multichannel detector and the following slit system were used: a 2 mm divergence slit on the tube, and Soller slits (2.5 mm plate spacing) on both the tube and detector sides. During data acquisition, the samples were rotated at 60 rpm. The diffraction spectra were processed using Diffrac.Eva and Diffrac.Topas software packages.

Microhardness of the material was measured using a Pruftechnik KB50 SR microhardness tester by the recovered-imprint method under a 200 g (1.9 N) load.

Results and discussion

X-ray diffraction analysis revealed that the deposited material consists of the characteristic α- and β-phases, with HCP and BCC lattices, respectively (Fig. 3). Since the diffraction peaks of α′-martensite coincide with those of the α-phase, its presence in the structure cannot be unambiguously confirmed from the diffraction pattern. The amount of β-phase was found to be approximately 20 %.

Optical metallography of the bulk samples revealed no macroscopic defects. After direct laser deposition, the α-phase appears as regions of basket-weave mor-

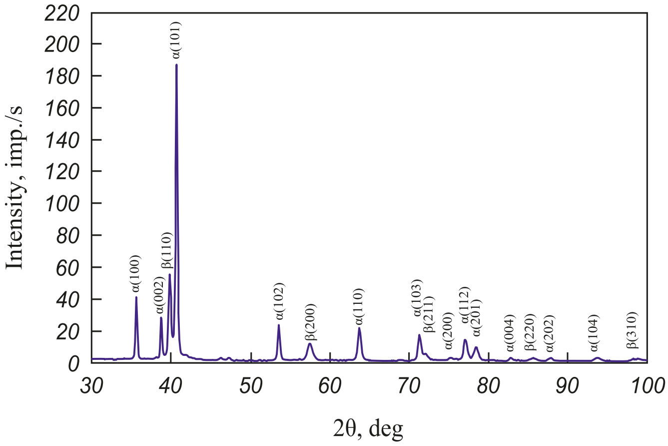

Fig. 3. *X*-ray pattern of VT23 alloy obtained by direct laser deposition

Рис. 3. Дифрактограмма сплава ВТ23, полученного прямым лазерным выращиванием

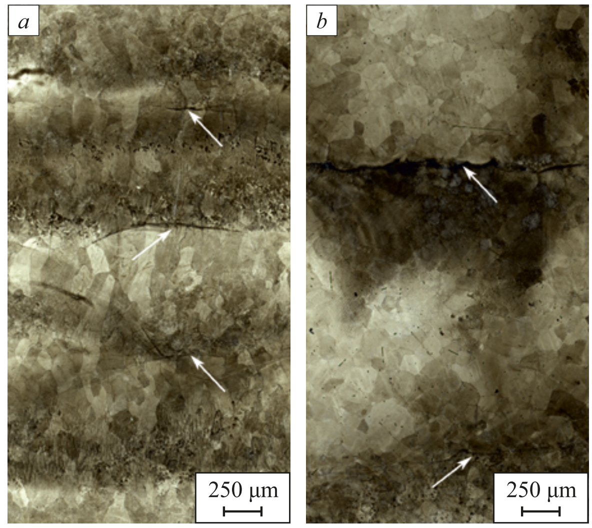

Fig. 4. Microstructure of VT23 alloy after direct laser deposition: *a* – laser scanning direction; *b* – sample deposition direction

Рис. 4. Микроструктура сплава ВТ23 после прямого лазерного выращивания: *a* – направление сканирования лазера; *b* – направление роста образца

phology and as a network along the boundaries of primary β-grains – features typical of this alloy both in the quenched state and after deposition [1 – 3; 8; 18 – 20]. In the scanning plane, large (~100 μm) equiaxed regions of primary β were observed.

Fig. 4 shows two types of bands distinguished by their etching contrast. According to the literature, the wide dark regions correspond to thermal-affected bands, while the narrow lines indicated by arrows are interlayer bands [18 – 20]. The thermally affected bands form in overlap zones of adjacent layers, where repeated thermal exposure during successive passes induces reheating and recrystallization, producing the observed etching contrast. The interlayer bands are regularly spaced and trace the boundaries of individual melt pools.

As noted in [19], the formation of interlayer bands depends on the degree of alloying and the rate of diffusion processes in titanium alloys.

The grain morphology of the obtained material also deserves attention. During deposition, non-uniform nucleation occurs on partially melted powder particles within the melt pool, resulting in the formation of fine equiaxed grains. Subsequently, epitaxial growth develops: grains grow from the bottom of the melt pool, inheriting the structure of the underlying layer, which produces large columnar grains. The final grain morphology is therefore determined by the competition between these two mechanisms [20].

Structural examinations revealed heterogeneity in the size of structural constituents, as the material consists of a combination of large columnar and small equiaxed grains. This heterogeneity might suggest a non-uniform distribution of microhardness throughout the volume. However, the measurements showed that the microhardness of the deposited material is homogeneous throughout the deposited samples.

Additionally, the microhardness of the VT23 titanium alloy produced by direct laser deposition varied slightly with build direction and averaged 485 ± 5 $HV_{0.2}$ along the laser scanning direction (*XY*) and 490 ± 20 $HV_{0.2}$ along the sample deposition direction (*XZ*).

Conclusions

The direct laser deposition (DLD) technology enables the fabrication of defect-free VT23 titanium alloy samples.

X-ray diffraction analysis confirmed that the deposited alloy consists of α- and β-phases; however, differentiation between the α- and α′-phases is difficult due to the similarity of their crystal lattices.

The structure of the obtained alloy exhibits regions of different etching contrast, which most likely indicates recrystallization during deposition. The microstructure is represented by a basket-weave arrangement composed of randomly oriented α-phase plates.

The average microhardness of the material does not vary from the substrate to the top surface and remains at approximately 488 ± 10 $HV_{0.2}$ both along the laser scanning direction and along the sample deposition direction.

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Yu. Yu. Ponkratova – complex metallographic study.

A. V. Alekseev – formation of research samples.

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