Metallophysics and Advanced Technologies
Металофіз. новітні технол.
Metallofiz. Noveishie Tekhnol.
2022, vol. 44, No. 3, pp. 383–391
https://doi.org/10.15407/mfint.44.03.0383
Reprints available directly from the publisher

PACS numbers: 61.80.Ba, 62.20.Qp, 64.60.My, 81.30.Kf, 81.40.Gh, 81.65.Lp

Laser Surface Strengthening of Heat-Resistant Titanium Alloy for Gas Turbine Engines

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The structural-phase state of the surface layers of the heat-resistant two-phase titanium alloy VT-8 after laser treatment in different gaseous environments is studied by the XRD and metallographic analyses. It is found out that laser melting in the atmospheres of argon, nitrogen and air leads to structural changes in the surface layers, which leads to their microhardness increase. It is shown that during laser treatment in an argon atmosphere a complete polymorphic $\beta \to \alpha'$-transformation by the martensitic mechanism occurs, which together with the raising in the degree of structure dispersion leads to an increase in microhardness values from 2.99 GPa to 5.62 GPa. During laser melting in nitrogen and air atmospheres, the change in the microhardness of the treated surfaces is due to the complex influence of several factors: increasing the degree of dispersion of the structure, formation of high-strength cubic titanium nitrides of TiN type and formation of supersaturated solid solutions of nitrogen and oxygen in α-titanium lattice. These factors cause an increase in the microhardness of the surface layers of the laser melting zone to 7.82 GPa (in a nitrogen atmosphere) and 6.56 GPa (in an air atmosphere).

Key words: laser treatment, melting zone, martensitic transformation, microhardness, phase composition.

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Citation: V. V. Girzhon, O. V. Smolyakov, O. V. Ovchinnikov, and O. V. Zavgorodny, Laser Surface Strengthening of Heat-Resistant Titanium Alloy for Gas Turbine Engines, *Metallofiz. Noveishie Tekhnol.*, **44**, No. 3: 383–391 (2022).
DOI: 10.15407/mfint.44.03.0383

Методами рентґенівського фазового та металографічного аналізів досліджено структурно-фазовий стан поверхневих шарів жаростійкого двофазного титанового стопу ВТ-8 після лазерної обробки в різних газових середовищах. Встановлено, що лазерне обтоплення в атмосферах арґону, азоту та повітря призводить до структурних змін у поверхневих шарах, внаслідок чого відбувається зростання їхньої мікротвердості. Показано, що у разі лазерної обробки в атмосфері арґону відбувається повне поліморфне $\beta \to \alpha'$-перетворення за мартенситним механізмом, що разом зі зростанням ступеня дисперсності структури призводить до підвищення значень мікротвердості з 2,99 ГПа до 5,62 ГПа. Під час лазерного обтоплення в атмосферах азоту та повітря зміна мікротвердості оброблених поверхонь відбувається внаслідок комплексного впливу декількох факторів: підвищення ступеня дисперсності структури, утворення високоміцних кубічних нітридів титану типу TiN та формування пересичених твердих розчинів втілення Нітроґену та Оксиґену у ґратниці α-титану. Перераховані чинники викликають зростання мікротвердості поверхневих шарів зони лазерного обтоплення до 7,82 ГПа (в атмосфері азоту) та 6,56 ГПа (в атмосфері повітря).

Ключові слова: лазерна обробка, зона обтоплення, мартенситне перетворення, мікротвердість, фазовий склад.

(Received November 30, 2021; in final version, March 3, 2022)

1. INTRODUCTION

At present titanium alloys are one of the main constructional materials used in various industries. Applications of titanium and its alloys are associated with their unique properties: high specific strength, corrosion resistance in many aggressive environments, elevated heat resistance. However, along with the positive parameters titanium alloys have some characteristics (including low hardness values), which limit their usage as constructional materials.

Alloying and heat treatment do not allow significant increase in antifriction properties of titanium alloys. There have been some reported trials to eliminate this shortcoming by chemical-thermal processes. The largest success has been achieved in nitriding of surfaces [1–6]. This technology, although limited, is widely used in industry. The main disadvantages of the treatment are low productivity, high energy consumption and insufficient depth of a reinforced layer.

One of the promising routes to improve mechanical properties of surface layers for titanium alloys is heating and cooling at high speeds, in particular laser treatment [7–14]. Known traditional technologies for surface strengthening are quenching, cementation, nitriding, nitrocementation, hard alloy cladding techniques. Compared with all these methods surface modification by laser has following advantages for friction parts: possibility of local processing for a required areas, fast heating and cooling of a treated zone, high manufacturability of process. At present the number of studies of surface structure formation in such treatments is still insufficient. In addition, investigations of laser treatment of surface layer structure formation in different gas environments still remain incomplete.

Therefore, the purpose is to study the structural state, phase transformations and microhardness changes in the surface layers of heat-resistant alloy VT-8 (Russia), which is close in chemical composition to alloy TC11 (USA), after laser treatment in argon, nitrogen and air.

2. EXPERIMENTAL/THEORETICAL DETAILS

Samples of industrial titanium alloy VT-8 in the form of forged rods with a diameter of 10 mm are selected as a starting material. The chemical composition of the alloy is given in Table 1.

Samples for research are cut in the form of cylinders with a height of 5 mm from the initial rods. Laser treatment (LT) was performed on a pulsed YAG laser QUANT-12 (1.06 μm) in a protective atmosphere of argon, air and nitrogen. The corresponding gas is supplied in the form of a jet directly into the LT zone. The radiation power density is 0.8–1.0 GW/m^2; pulse duration—$\tau = 4\cdot 10^{-3}$ s. The diameter of the laser spot depending on the degree of defocusing of the beam ranged from 0.8–1.0 mm. Changing the degree of overlap of the laser spots is achieved by varying the frequency of the pulses. The phase composition of the surface layers of the samples after LT and the morphological features of the surface layers are controlled diffractometrically (MiniFlex Rigaku, CuK_α radiation) and metallographically (Epiquant).

3. RESULTS AND DISCUSSION

According to X-ray phase analysis, the sample in the initial state has two phases. Reflections from h.c.p. α-titanium and cubic β-titanium lattices are detected (Fig. 1, *a*).

LT in argon led to a change in the phase composition. In this case reflections only from α-phase lattice are found (Fig. 1, *b*). The absence of β-phase in the surface layers is due to rapid metal cooling from β-region. Thus, it is no diffusion process but rather martensitic $\beta \to \alpha'$-

TABLE 1. Chemical composition of titanium alloy VT-8.

Ti	Chemical elements, % wt.									
	Al	Mo	Zr	Si	Fe	C	O	H	N	Other
Basis	5.8–7.0	2.8–3.8	0.5	0.2–0.4	0.3	0.1	0.15	0.015	0.3	0.3

transformation. Alloying elements dissolved in α-Ti lattice have stabilized α-phase. It is known [15] that α′-phase, which is formed in martensitic transformation, is a supersaturated solid solution of alloying elements in α-titanium. It has hexagonal lattice and a needle martensitic structure.

Precise measurements of lattice parameters for α-phase after laser treatment in argon show their decrease compared to the original sample (Table 2). This can be explained as following: $\beta \rightarrow \alpha'$-transformation results a formation of supersaturated substitution solid solution of molybdenum in α-Ti lattice. Since atomic radii of molybdenum are smaller compared with that of titanium, it is feasible to assume that lattice parameters of α-phase will decrease.

After LT in nitrogen reflections from three lattices are present on the diffraction patterns: α-titanium, cubic TiN and weak peaks from β-titanium (Fig. 1, *c*). The presence of a small β-phase amount can be explained by the following. The laser melting zone is chemically heterogeneous. Therefore, in the areas heavily enriched with nitrogen, two phases are formed: α-Ti and TiN. In this case β-phase will not be

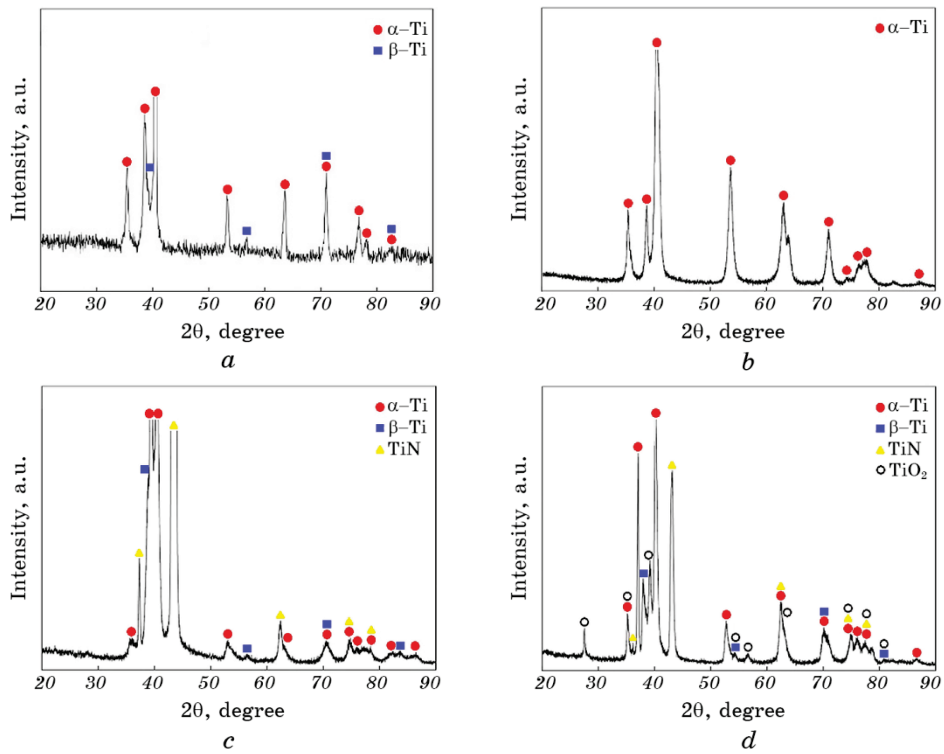

Fig. 1. XRD profiles from the surface layers of VT-8 alloy in the initial state (*a*) and after laser melting in argon (*b*), nitrogen (*c*), air (*d*).

formed at all because nitrogen is an effective stabiliser for α-phase [15, 16] according to Ti–N equilibrium diagram.

However, it could be feasible that in areas with less nitrogen, the β-phase is first formed. Then this phase decays by monothectoid mechanism and formation of molybdenum-stabilised BCC β-phase + α-Ti. Since the total picture of phase composition in surface layers with a depth of about 25–30 μm is displayed in XRD analysis, all three phases are visible on diffractograms.

Precise measurements of α-phase lattice parameters after LT in nitrogen showed an increase in them (Table 2). This could be due to the following reasons. Solubility of nitrogen [16] in α-titanium is about 3 at.% at room temperature. At larger temperatures it is much higher and can reach 22 at.%. In process of laser melting, a cooling rate of the melt is approximately 10^4 K/s. This makes it possible to obtain the high-temperature structure at room temperature. Obtained state is a supersaturated solid solution of nitrogen in α-Ti, which is the reason for the increase in lattice parameters.

It should be mentioned that two competing processes probably took place in LT under nitrogen. On the one hand, atoms of molybdenum, aluminium, and iron could replace titanium in the lattice. This would lead to a decrease in the parameters of the crystal lattice. On the other hand, some of nitrogen atoms could be embodied in octahedral pores of hexagonal lattice. This would augment parameters of the lattice. It is obvious that the formation of an embodiment solid solution influences changes in lattice parameters more compared with atom replacement. Thus, it causes the growth of α-phase parameters compared with the original sample (see Table 2).

During laser melting of the sample surface in air, four phases are found: α-Ti, β-Ti, tetragonal TiO_2 and cubic TiN (Fig. 1, *d*). In this case weak reflections from the lattice of β-phase are also present on the XRD-patterns. The reasons for their presence are similar to the treatment in nitrogen (see the above).

After LT in air, an increase in the parameters of α-Ti is also observed

TABLE 2. Lattice parameters α-Ti of VT-8 alloy after laser surface treatment in different atmospheres.

Lattice parameters, nm			
Initial state	LT in an argon atmosphere	LT in a nitrogen atmosphere	LO in the air atmosphere
$a = 0.29323 \pm$ ± 0.00001 $c = 0.46807 \pm$ ± 0.00009	$a = 0.29313 \pm$ ± 0.00008 $c = 0.46738 \pm$ ± 0.00009	$a = 0.29501 \pm$ ± 0.00008 $c = 0.47179 \pm$ ± 0.00019	$a = 0.29501 \pm$ ± 0.00008 $c = 0.47394 \pm$ ± 0.00019

(Table 2). According to [17] in Ti–O system, solubility of oxygen at room temperature in α-titanium is approximately 10 at.%. At high temperatures it reaches 35 at.%. Thus, at room temperature, a supersaturated solid solution of atmospheric gases (oxygen and nitrogen) in titanium lattice can be formed after rapid cooling. This causes an increase in the parameters of α-phase lattice.

Measurements of surface microhardness showed its growth compared with the initial state after LT in all studied atmospheres (Table 3). The change in the values of microhardness after LT in argon is associated with two factors: martensitic $\beta \rightarrow \alpha'$-transformation ($\alpha'$-phase has a higher value of microhardness compared to α-phase [18]) and augmenting of dispersion degree in the structure.

The increase in microhardness after LT in nitrogen and air is explained by the following: martensitic $\beta \rightarrow \alpha'$-transformation, increasing the degree of structure dispersion, solid-solution hardening due to embodiment of oxygen and nitrogen atoms in titanium h.c.p. lattice, titanium nitride formation. It should be noted that the values of microhardness after LT in air are slightly lower compared with those ones obtained in nitrogen. This is explained by higher concentration of TiN after LT in nitrogen which ultimately yielded an increase in total microhardness.

Significant difference between the exterior surfaces melted in different gas environments is observed. Thus, treatment in an argon environment (Fig. 2, *a*) led to the formation of the almost mirror laser spots on the surface of the samples. More or less contrasting image of such spots could be observed only in side lighting. At the same time, a weakly pronounced relief in the form of concentric circles is observed on the spots surface, which is detected earlier in [19].

The presence of significant amounts of titanium nitride in the surface layers after melting in an environment of nitrogen led to a golden colour laser spots and the formation of more advanced relief (Fig. 2, *b*). This is due to the fact that TiN nitride is a refractory compound (2930°C) and the formation of the surface macrostructure occurred very quickly, almost during the action of the radiation pulse ($\tau = 4\cdot10^{-3}$ s). It gave no possibility for surface tension forces to smooth the sur-

TABLE 3. The phase composition of the samples and surface microhardness of alloy VT-8 after LT in various gas atmospheres.

Type of treatment	Phase composition	Microhardness of the surface, GPa
Initial state	α-Ti, β-Ti	$H_\mu = 2.99 \pm 0.02$
LT in an argon atmosphere	α-Ti	$H_\mu = 5.62 \pm 0.04$
LT in a nitrogen atmosphere	α-Ti, β-Ti, TiN	$H_\mu = 7.82 \pm 0.18$
LT in the air atmosphere	α-Ti, β-Ti, TiN, TiO_2	$H_\mu = 6.56 \pm 0.09$

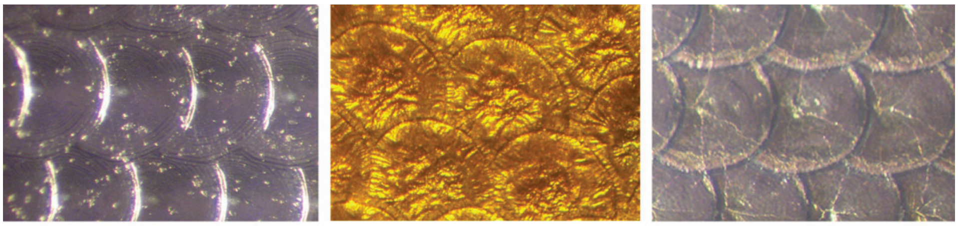

Fig. 2. Macrostructure of the surface of VT-8 alloy after laser melting in argon (*a*), nitrogen (*b*) and air (*c*).

face of the laser spot.

A characteristic feature of the spots after melting in the air is the lack of a shiny surface and the presence of light areas on the periphery of the spot. This feature can be explained by the following reasons. At high temperatures, the formation of refractory nitride TiN initially occurred. According to [20], the TiN phase actively reacts with oxygen at high temperatures. Then, when the temperature decreased to the temperature of TiO_2 oxide existence (<1860°C [17]), the oxidation of nitride began with the formation of an oxide film on the surface. The presence of light-colored areas on the periphery of the spots is explained by two factors: firstly, lower temperatures in these areas due to Gaussian energy distribution on the surface of the spots and, secondly, higher cooling rates of the melt, which did not allow sufficient oxidation. That is, light areas can be identified as a mixture of nitride and oxide.

According to metallographic analysis in the initial state grain size of α-Ti is about 3 μm, β-Ti—1.5 mm (Fig. 2, *a*).

LO in an argon atmosphere (Fig. 3, *b*) led to a change in the structure—in the surface cross-sections of the laser melting zone only the structural components of the needle shape typical for the α′-phase are

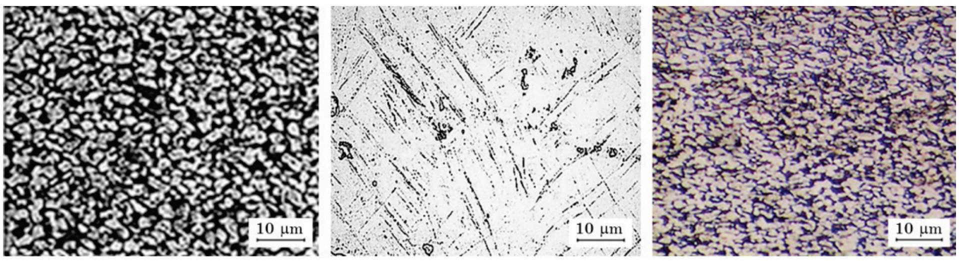

Fig. 3. The structure of the initial alloy VT-8 (*a*) and the surface layers of the cross section of the laser melting zone in an argon (*b*), and nitrogen (*c*).

observed *i.e.*, the martensitic nature of the $\beta \rightarrow \alpha'$-transformation is confirmed.

Metallographic studies of the sample after LT in nitrogen (Fig. 2, *c*) detected an increase in structure dispersion compared with original metal. It is impossible to detect the inclusion of nitrides by optical metallographic analysis.

For all treatments, the structure is almost homogeneous for the entire depth of the laser melting zone (180–200 μm).

Thus, LT of VT-8 alloy increases microhardness of the surface layers. This is caused by high cooling rates of the melt which affect final metal structure.

4. CONCLUSION

1. Due to the high cooling rates of the melt during surface laser treatment of the two-phase alloy VT-8 in argon a complete polymorphic $\beta \rightarrow \rightarrow \alpha'$-transformation by the martensitic mechanism occurs, which together with increasing degree of dispersion of the structure leads to an increase in microhardness from 2.99 GPa to 5.62 GPa.
2. Laser treatment of VT-8 alloy in nitrogen and air causes an increase in microhardness in the surface layers of melted metal to 5.23 GPa and 4.49 GPa, respectively. This is due to simultaneous action of several factors: increasing of dispersion degree in the structure, formation of high-strength cubic titanium nitrides and development of supersaturated solid solutions with nitrogen and oxygen in α-titanium lattice.

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