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Diode laser surface modification of Ti6Al4V alloy to improve erosion wear resistance

A. Lisiecki*, A. Klimpel
Welding Department, Silesian University of Technology,
ul. Konarskiego 18A, Gliwice 44-100, Poland
* Corresponding author: E-mail address: aleksander.lisiecki@polsl.pl

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ABSTRACT

Purpose: Purpose of this paper : The purpose of the study was to develop new laser alloying technology providing high erosion wear resistance of the working surfaces of blades made of titanium alloy Ti6Al4V.

Design/methodology/approach: High power diode laser HPDL with a rectangular laser beam spot of multimode and uniform intensity of laser radiation was applied in the process of laser surface modification of the titanium alloy Ti6Al4V. During the laser surface remelting and alloying of the titanium alloy in argon and nitrogen atmospheres, surface layers of high hardness and significantly higher erosion wear resistant, compared with the base material of titanium alloy Ti6Al4V, were produced.

Findings: The surface layers are composites of titanium nitrides participations in the titanium alloy matrix. Hardness of the surface layers and erosion wear resistance depends strongly on parameters of laser processing and on the partial pressure of nitrogen in the gas mixture of nitrogen-argon atmosphere.

Research limitations/implications: The most critical parameter of the functional quality of titanium alloy blades of turbofan engine and steam turbines is the fatigue strength, therefore further investigations are required to determine the fatigue strength and also internal stresses in the nitrided surface layers.

Practical implications: The novel technology of high power diode laser surface modification of the titanium alloy Ti6Al4V can be applied to produce erosion wear resistant and long lifetime surface layers of turbofan engine blades and steam turbine blades.

Originality/value: The laser surface modification of titanium alloy by the high power diode laser with the rectangular laser beam spot of multimode and uniform intensity of laser radiation is very profitable in a case of laser surface remelting and alloying because the treated surface is heated uniformly, so uniform penetration depth and uniform thickness of the surface layer can be achieved, as opposed from circular laser beams of solid states YAG and gas lasers.

Keywords: Laser Surface Alloying, LSA; Laser Gas Nitriding, LGN; titanium alloy

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Over 50 [%] of rotating parts of modern aircraft turbofan engines are made of titanium alloys. The aircraft turbofan engine consists of two main sections: the fan and the gas turbine, Fig. 1. The fan section is responsible for the intake and compression of cold air. Usually, the fan section have three stages of compression. The first is a large spinning fan which sucks in large quantities of air, next the turbine of initial compression compressor (low pressure) and the turbine of high pressure compressor, Fig. 1, 2. In the gas turbine section a combustion chamber is placed [1,8,9,18].

Diameter of the fan rotor, including the blades, can exceed 1,5 [m], and it rotates at several thousand revolutions per minute. The fan sucks in air at ambient temperature. The air coming into the engine is compressed by rotating blades pushing the air against stationary vanes. As the air is compressed, it heats up.

Depending on how many compressor stages the engine has and what the total compression is, the air can be compressed to 40 atmospheres and the temperature at the last stage of compressor can reach 400÷600 [°C], Fig. 2 [1,2,3,18].

Initially, rotors and fan blades of turbofan engines were made of stainless steel, then replaced by nickel and cobalt superalloys and aluminum alloys of lower specific weight, so the mass of rotating parts of engine could be reduced significantly [1,3,4,18].

Currently, titanium alloys ara widely used for manufacturing of rotors and fan blades of modern turbofan engines. Titanium and its alloys are favored because of its light weight, high strength to weight ratio, high corrosion resistance and good high cycle fatigue properties [3,5,6,15,18].

The most resent achievement at manufacturing of fan blades is application of titanium matrix composite - TMC. The titanium matrix is reinforced with silica carbides fibers. The composites have great mechanical properties, high durability, low specific weight, but similarly to titanium and titanium alloys the erosion and cavitations resistance is not satisfactory. The composites have great mechanical properties, high durability, low specific weight, but similarly to titanium and titanium alloys the erosion and cavitations resistance is not satisfactory. According to the prognosis, future planes may use fans with polymer (plastic) matrix or ceramic matrix composite (CMC) blades [7,11,12].

Laser Surface Alloying (LSA) is a process of enriching of surface layers of materials by alloying elements and/or transformation of the surface layer's structure [10÷18]. There are fallowing techniques of the laser surface alloying [10]:

- Laser Surface Remelting (LSR) of the substrate material with a layer of preplaced additional material in the form of paste, electrolytic coatings, plasma or flame sprayed coatings,
- Laser Surface Melting (LSM) of the substrate material and simultaneously injecting of the additional material, in the form of powder, directly into the weld pool,
- Laser Surface Melting of the substrate material in an active gas atmosphere, e.g. nitrogen – Laser Gas Nitriding (LGN).

The purpose of the study was to develop new laser alloying technology providing high erosion wear resistance of the working surfaces of blades made of titanium alloy Ti6Al4V, Table 1, 2.

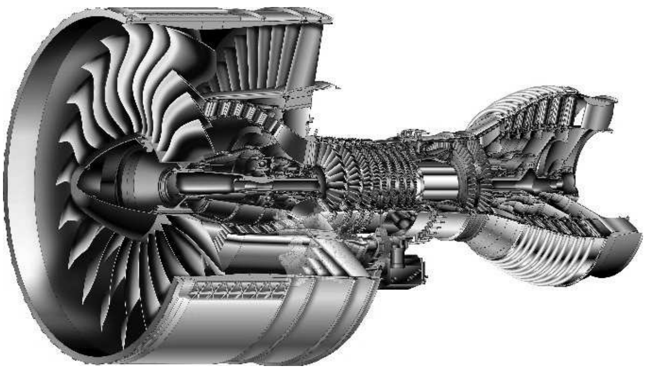

Fig. 1. A view of the aircraft turbofan engine GP 7000 Pratt& Whitney used in Airbus A380 [1,2,18]

2. Experimental

To produce erosion wear resistant and high hardness surface layers of turbofan engine blades and steam turbine blades made of titanium alloy Ti6Al4V laser gas nitrating (LGN) technology of laser alloying was selected to create titanium nitrides participations in the titanium alloy matrix surface layers. Table 1. The specimens of titanium alloy Ti6Al4V sheet 1,5 [mm] thick were cut into coupons 50,0x100,0 [mm].

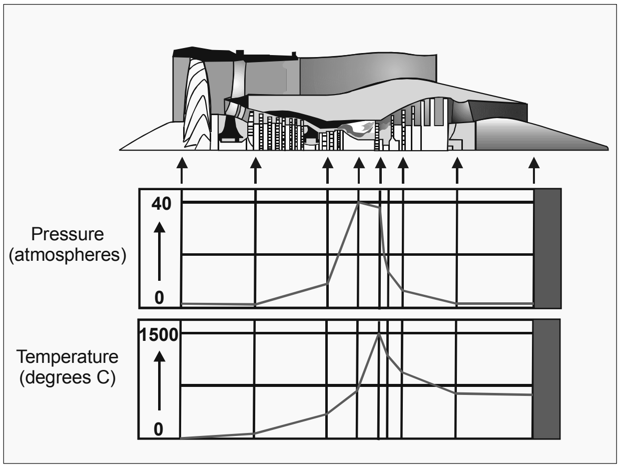

Fig. 2. Temperature and pressure distribution across the turbofan engine [2,18]

To ensure full control of the gas atmosphere during laser alloying of surface layers, the specimens of titanium alloy were placed into a gas chamber filled in by the mixture of high purity (99,999 [%]) argon and nitrogen at different partial pressures, controlled by precise electronic gas mixing device, Table 4. Alloying process was conducted in the pure argon atmosphere to produce reference surface layers to nitrated surface layers and the process has to be recon as the surface laser remelting process. Continuous flow of the gas mixture was kept through the gas chamber at flow rate 10,0 [l/min] and pressure 1,0 [atm]. Flow of the argon and nitrogen mixture was switched on 90 [s] prior to the laser alloying process, to remove air from the gas chamber.

Trials of laser alloying of the titanium alloy specimens were conducted on fully automated CNC stand equipped with the high power diode laser HPDL ROFIN DL 020, Table 3, Fig. 3. The rectangular laser beam spot of multimode, uniform intensity of laser radiation is very profitable in a case of laser surface remelting and alloying, because the treated surface is heated uniformly. The surface layers of the titanium alloy specimens were produced as single stringer beads, and laser beam was focused on the top of specimens, and the long side of the laser beam spot was set perpendicularly to the alloying direction, Fig. 4. Surface of titanium alloy specimens was prepared by mechanical removing surface oxide layer and next degreasing it by acetone just prior the laser alloying.

Tests of erosion wear resistance were conducted in accordance to ASTM 76 standard at velocity of the erodent particles stream 70 [m/s], at angles 90 [°] and 30 [°], to simulate the real wear conditions of working surfaces of turbofan engine blades and steam turbine blades, mounted on the engine rotor at an inclination angle about 30 [°] to the direction of rotating. Tests of erosion wear were conducted on the surface layers of titanium alloy specimens after laser alloying at different parameters, and also on the surface of titanium alloy sheet (base metal), which was the reference sample to determine the relative resistance to erosion wear, Fig. 19, 20.

Table 1.
Chemical composition of titanium alloy Ti6Al4V, Table 2

Alloying element	Al	V	Fe	C	Si	Mn	Mo	Cu	B	Zr	Sn	O	H
Content [%]	6.29	4.12	0.18	0.14	0.1	0.01	0.1	0.02	0.01	0.1	0.01	0.19	0.0032

Table 2.
Physical properties of titanium alloy Ti6Al4V, Table1

Property	Density [g/cm^3]	Melting point [°C]	Specific heat [J/kg·K]	Thermal expansion coefficient	Electrical resistance [Ω·cm]	Thermal conductivity [W/m·K]
Value	4.42	1649	560	$8.6 \cdot 10^{-6}$	170	7.2

Table 3.
Technical data of high power diode laser HPDL ROFIN SINAR DL 020, Fig. 3,4

Parameter	Value
Wavelength of the laser radiation - [nm]	808 ÷ 940 (±5)
Maximum output power of the laser beam (cw) - [kW]	2.2
Range of laser power - [kW]	0.1 ÷ 2.2
Focal length - [mm]	82 / 32
Laser beam spot size - [mm]	1.8×6.8/1.8×3.8
Range of laser power intensity - [kW/cm^2]	0.8 ÷ 32.5

Table 4.
Parameters of high power diode laser HPDL ROFIN DL 020 laser alloying of titanium alloy Ti6Al4V specimens in argon or mixture of argon and nitrogen atmosphere, Table 1, 2, Fig. 5 to 20

Specimen no.	Alloying speed [mm/min]	Heat input [J/mm]	Partial pressure of argon [atm]	Partial pressure of nitrogen [atm]	Penetration depth [mm]
P1	300	200	1.0	0.0	1.30
P2	700	86	1.0	0.0	1.15
P3	1100	55	1.0	0.0	0.55
P4	300	200	0.0	1.0	1.45
P5	1100	55	0.0	1.0	1.15
P6	1900	32	0.0	1.0	0.32
P7	1100	55	0.2	0.8	0.87
P8	1100	55	0.4	0.6	0.79
P9	1100	55	0.6	0.4	0.75
P10	1100	55	0.8	0.2	0.68

Remarks: Laser beam power 1000 [W], laser beam spot size 1.8x6.8 [mm], focal length 82 [mm], gas mixture flow rate 10.0 [l/min]

3. Results

The surface layers of titanium alloy Ti6Al4V specimens after laser alloying (remelting) in atmosphere of argon have silver colour and metallic shine, Fig. 5. The single stringer bead of the laser remelted layers is flat and smooth without any undercuts. The width of a single stringer bead, is from 5,5 to 6,5 [mm], depending strongly on laser power and speed of alloying, Table 4. The grain size in fusion zone of the surface layers after laser remelting in argon atmosphere is proportional to heat input. Increasing of the heat input of laser remelting resulted in increasing of the grain size, Fig. 7÷12.

In the case of surface layers after laser alloying in the gas mixture of argon and nitrogen at partial pressure over 0,3 [atm], the surface of laser nitrated layers are matt and have golden colour, characteristic for titanium nitrides, Fig. 6,8,14. Roughness of the surface layers increases with the increase of nitrogen partial pressure. The width, penetration depth and cross section area of the surface layers depends not only on parameters of laser alloying, but strongly depends on the partial pressure of nitrogen in the gas mixture as well, Fig. 6,8,14, Table 4. Increase of the partial pressure of nitrogen results in increase of the width and penetration depth of alloyed surface layer. The surface layers after laser alloying at laser power 1000 [W], alloying speed 1100 [mm/min] and at partial pressure of nitrogen 0,2 [atm] in the gas mixture, is about 4,9 [mm] wide, the penetration depth is 0,68 [mm] and the cross section area is 2,1 [mm²], Fig. 8, 15.

Increasing the partial pressure of nitrogen to 0,8 [atm] resulted in increasing width of the alloyed surface layer to over 5,5 [mm], penetration depth to 0,86 [mm] and cross section area to 3,25 [mm²], Table 4. When pure nitrogen atmosphere was used in laser alloying process the alloyed surface layers of max width 6,0 [mm], penetration depth 1,15 [mm] and max cross section area 7,5 [mm²], were produced, Fig. 15. Table 4.

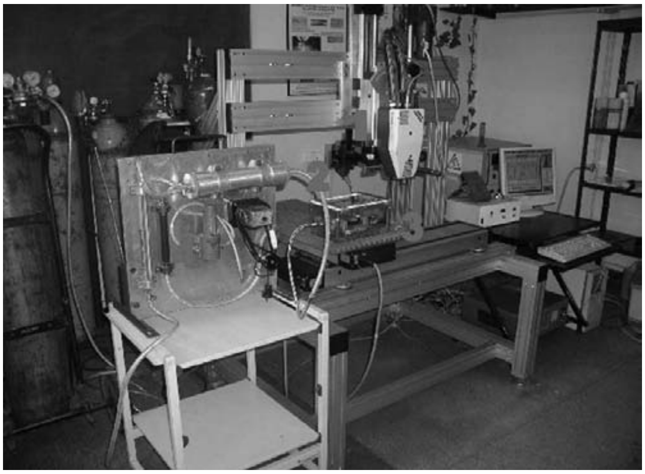

Fig. 3. Automated set up for laser alloying; 1) high power diode laser HPDL ROFIN SINAR DL 020, 2) gas chamber, 3) positioning system, 4) electronic gas mixer

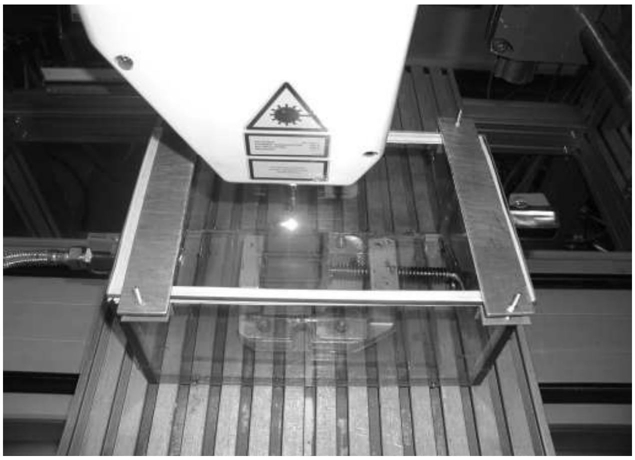

Fig. 4. A view of laser alloying (gas nitriding) of titanium alloy Ti6Al4V in a gas chamber filled in with argon and nitrogen mixture

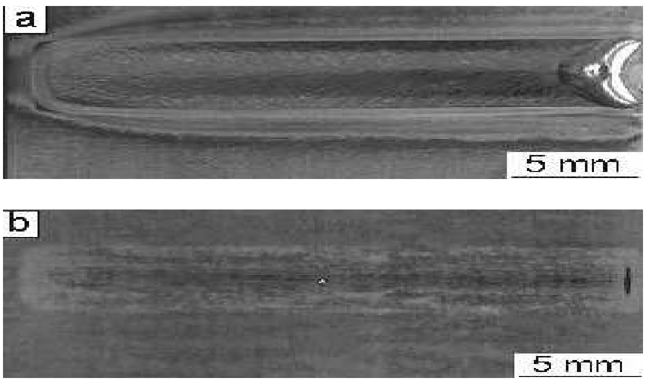

Fig. 5. A view of surface layers after laser remelting of titanium alloy Ti6Al4V in argon atmosphere by HPDL laser; a) sample P1, b) sample P3, Table 4

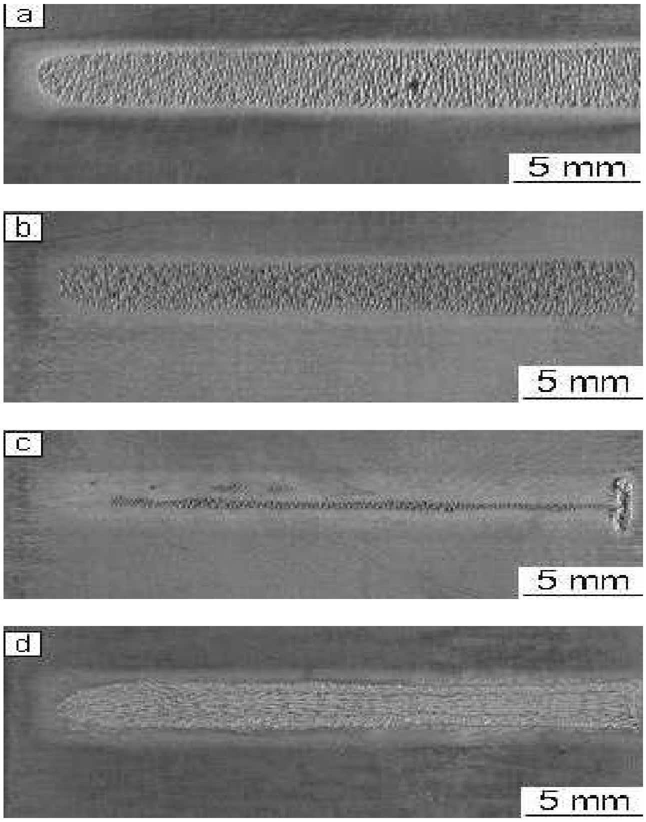

Fig. 6. A view of surface layers after laser alloying of titanium alloy Ti6Al4V in nitrogen and argon-nitrogen mixture atmosphere; a) sample P4, b) sample P5, c) sample P7, d) sample P9, Table 4

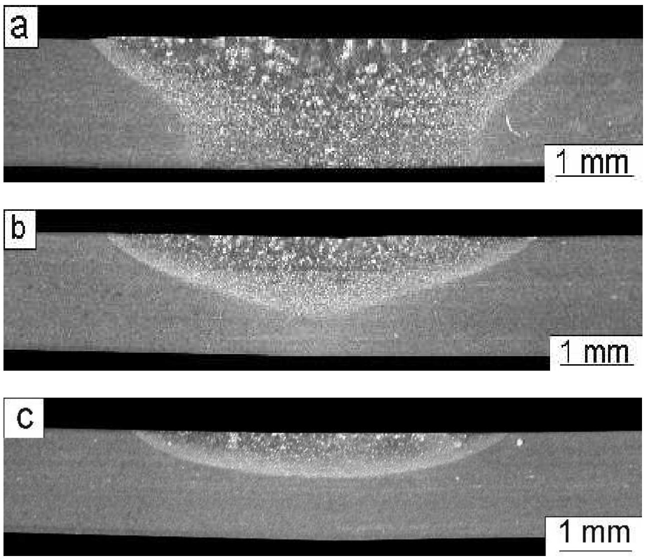

Fig. 7. Macrostructure of surface layers after HPDL laser remelting of titanium alloy Ti6Al4V in argon atmosphere; a) sample P1, b) sample P2, c) sample P3, Fig. 13, Table 4

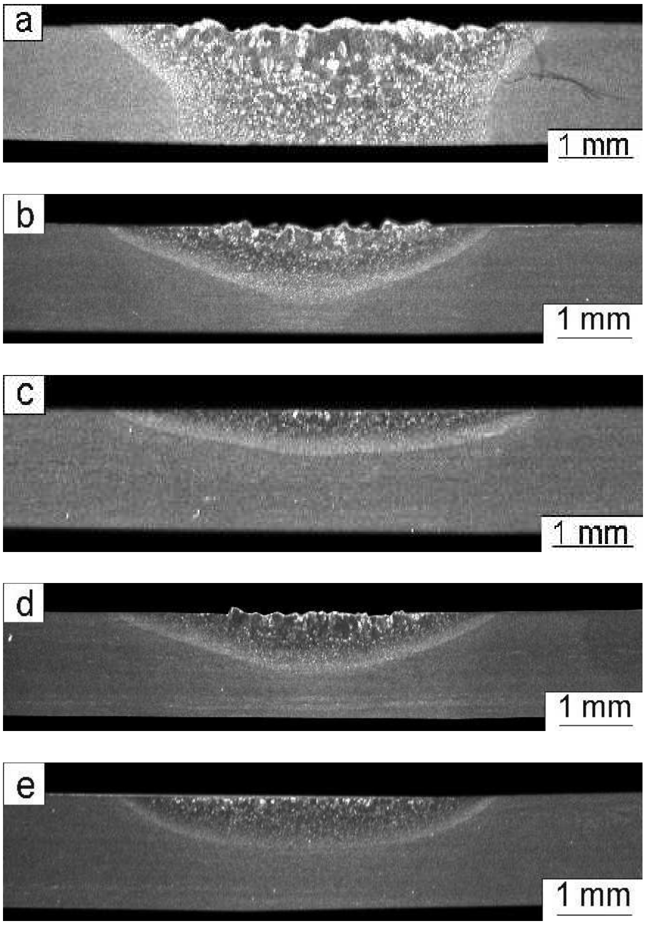

Fig. 8. Macrostructure of surface layers after HPDL laser alloying of titanium alloy Ti6Al4V in nitrogen and argon-nitorgen mixture atmosphere;
a) sample P4, b) sample P5, c) sample P6, d) sample P7, e) sample P9, Fig. 14, Table 4

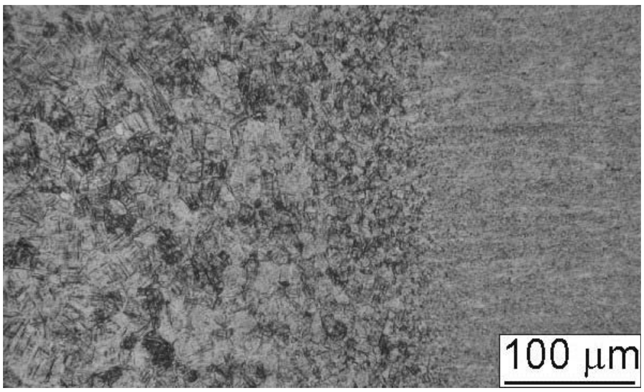

Fig. 9. Microstructure of a surface layer after HPDL laser alloying of titanium alloy Ti6Al4V in nitrogen atmosphere, Sample P6 (from left: fusion zone, heat affected zone and base material), Table 4

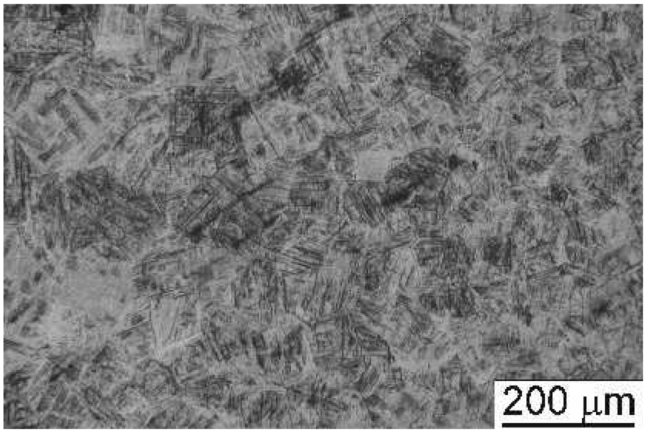

Fig. 10. Microstructure of a surface layer after HPDL laser remelting of titanium alloy Ti6Al4V in argon atmosphere, Sample P2 (fusion zone), Fig. 13, Table 4

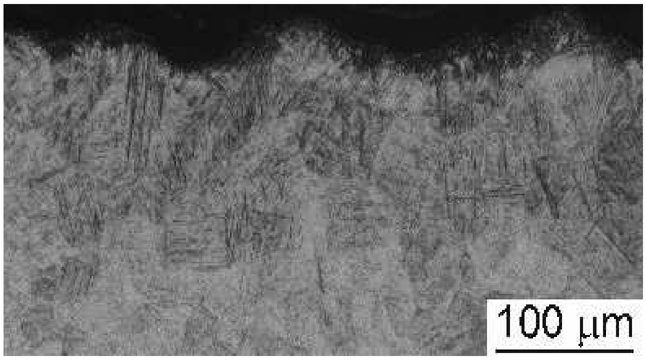

Fig. 11. Microstructure of a surface layer after HPDL laser alloying of titanium alloy Ti6Al4V in nitrogen atmosphere, Sample P5 (under surface), Fig. 14, Table 4

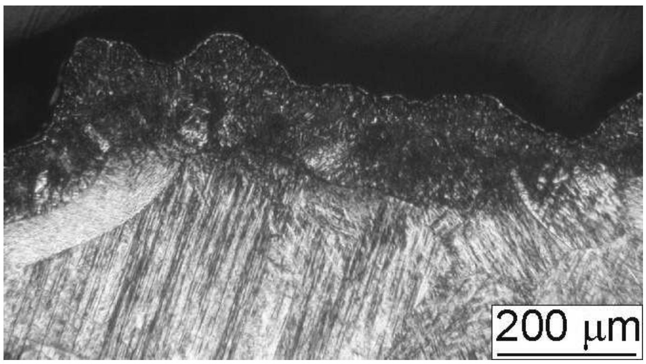

Fig. 12. Microstructure of a surface layer after HPDL laser alloying of titanium alloy Ti6Al4V in nitrogen atmosphere, Sample P5 (surface layer of TiN), Fig. 14, Table 4

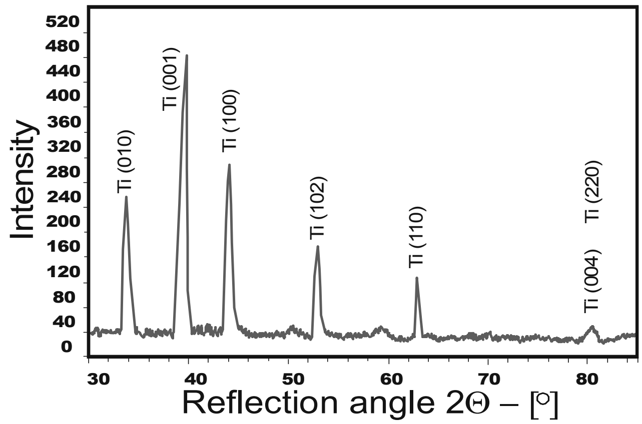

Fig. 13. XRD spectrum of the surface layer after HPDL laser remelting of titanium alloy Ti6Al4V in argon atmosphere, Sample P2, Table 4

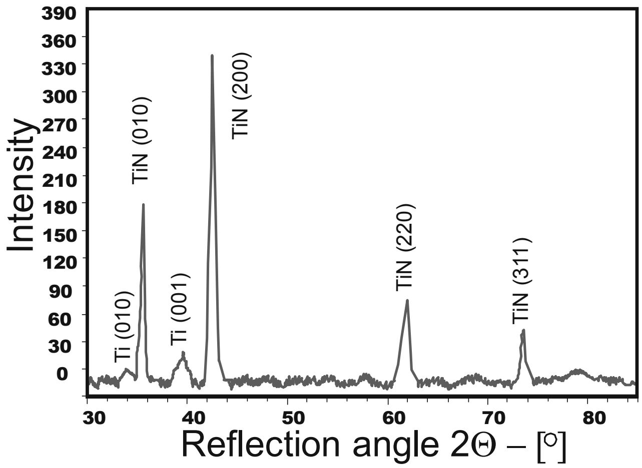

Fig. 14. XRD spectrum of the surface layer after HPDL laser alloying of titanium alloy Ti6Al4V in nitrogen atmosphere, Sample P5, Table 4

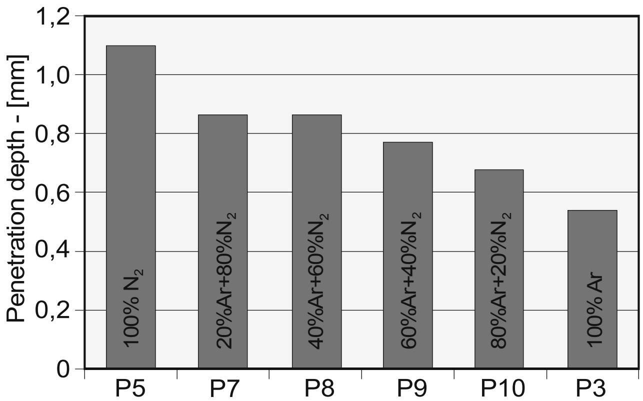

Fig. 15. Influence of the partial pressure of nitrogen in argon nitrogen mixture on penetration depth of the surface layer of titanium alloy, during diode laser alloying, Table 4

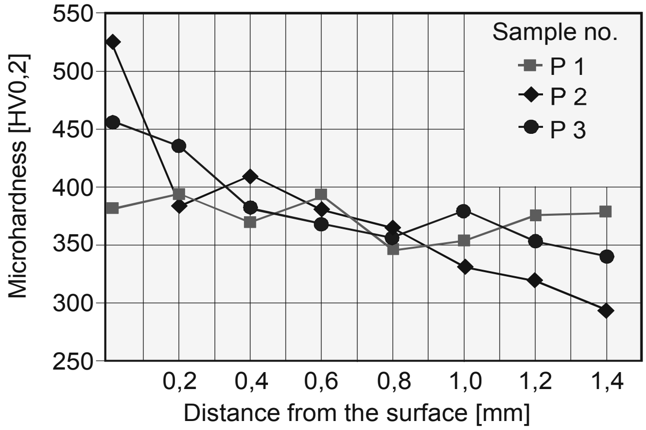

Fig. 16. Microhardness distribution on a cross section of the surface layer after HPDL laser remelting of titanium alloy Ti6Al4V in argon atmosphere, Table 4

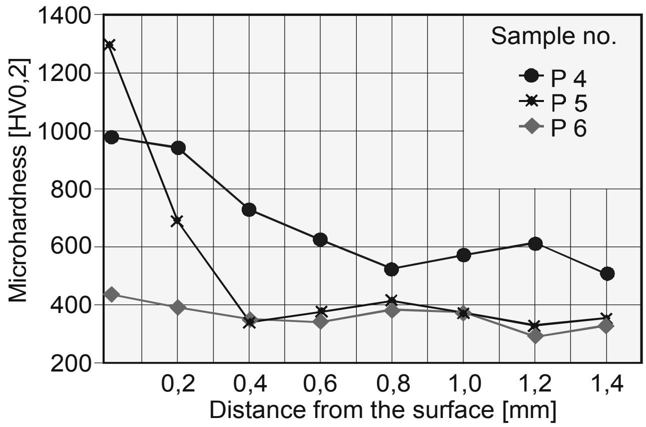

Fig. 17. Microhardness distribution on a cross section of the surface layer after HPDL laser alloying of titanium alloy Ti6Al4V in nitrogen atmosphere, Table 4

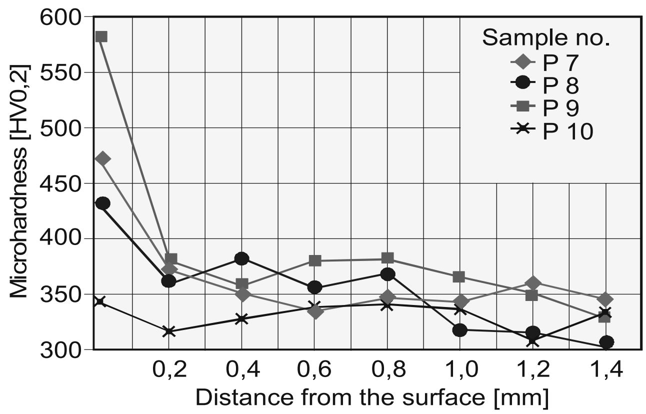

Fig. 18. Microhardness distribution on a cross section of the surface layer after HPDL laser alloying of titanium alloy Ti6Al4V in gas mixture of argon-nitrogen atmosphere, Table 4

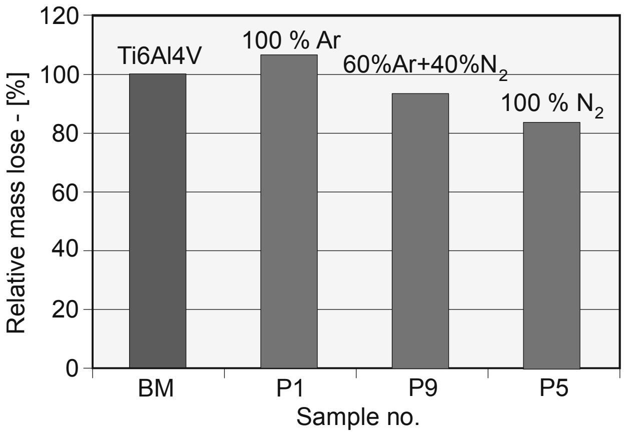

Fig.19. Erosion wear resistance of the surface layers after laser remelting and alloying of titanium alloy in argon, nitrogen and argon-nitrogen mixture, at the inclination angle of erodent particles stream 90 [°], Table 4

Penetration depths of the surface layers remelted in nitrogen atmosphere are about twice higher than in argon atmosphere, at the same parameters of remelting (alloying), Fig. 7,8,15. The reason of higher penetration depths in nitrogen atmosphere is the additional heat released during highly exothermic reactions of titanium nitrides TiN formation :

$$2Ti + N_2 = 2TiN + 82 \text{ [kcal/g·mol]} \quad (1)$$

Laser alloying of surface layers of the of titanium alloy Ti6Al4V specimens in atmosphere of argon and nitrogen mixture, at partial pressure of nitrogen up to 0,2 [atm], leads to increase of microhardness of the fusion zone of surface layer just at heat input below 70 [J/mm] and alloying speed over 700 [mm/min], Fig. 16,18. The highest microhardness of the fusion zone in a range 450÷490 [HV0,2], was measured directly under the surface of the alloyed surface layer, compared with microhardness of the base material 300÷340 [HV0,2], Fig. 16. The highest microhardness of the alloyed surface layer is up to 1300 [HV0,2] was produce at pure nitrogen atmosphere at the heat input 55 [J/mm], and alloying speed 1100 [mm/min], Fig. 17.

Laser alloying at the heat input below 50 [J/mm] and speed over 1500 [mm/min] leads to low penetration depth which does not exceed 0,30 [mm]. In this case the volume of weld pool is very low and the period when titanium stays in liquid phase is so short, that the saturation of titanium alloy by the nitrogen is very limited. Consequently, thickness of the alloyed surface layer with very hard titanium nitrides, is below 0,10, Table 4.

The resistance to erosion wear of the laser alloyed surface layers after of titanium alloy specimens in the argon atmosphere is similar to the resistance of base metal of titanium alloy Ti6Al4V and it does not depend on the inclination angle of erodent particles stream, Fig. 5. The highest resistance to erosion wear, show the surface layers after laser alloying in nitrogen atmosphere at heat input 55 [J/mm], Fig. 5. The resistance to erosion wear of the alloyed surface layer in pure nitrogen atmosphere, at the inclination angle of erodent particles stream 90 [°], is about 18 [%] higher than the erosion resistance of titanium alloy Ti6Al4V sheet, and increases up to 3 times at the inclination angle 30 [°] Fig. 19,20. This phenomenon is characteristic in a case of erosion wear of hard materials and it is a result of different mechanisms of wear, depending on the inclination angle of erodent particles stream [9]. The stream of erodent particles set perpendicularly to the surface of hard material causes micro cracks on the surface and splits off particles from the surface of hard material. In a case of low inclination angle of the erodent stream the surface of hard material is exposed to micro machining and abrasion, Hard materials generally show high resistance to this type of wear.

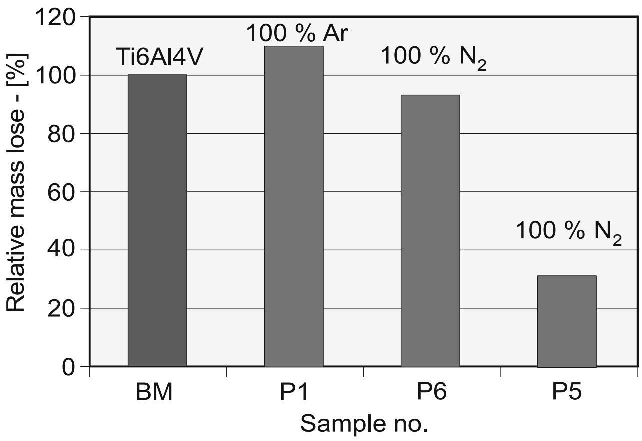

Fig. 20. Erosion wear resistance of the surface layers after laser remelting and alloying of titanium alloy in argon, nitrogen and argon-nitrogen mixture, at the inclination angle of erodent particles stream 30 [°], Table 4

4. Conclusions

The surface layers of titanium alloy Ti6Al4V sheet specimens after laser alloying (remelting) in argon atmosphere are flat, smooth and without any undercuts and have silver colour and metallic shine. The grain size in fusion zone of the surface layers after laser remelting in argon atmosphere is proportional to heat input. Increasing of the heat input of laser remelting resulted in increasing of the grain size. If the partial pressure of nitrogen, in the nitrogen-argon mixture, is over 0,3 [atm], the nitrated surface layer becomes rough and golden, characteristic appearance for titanium nitrides, and roughness increases with the increase of nitrogen partial pressure, Fig. 1,2.

The width, penetration depth and cross section area of the nitrated surfaced layers, depends not only on parameters of laser alloying, but strongly depends on the partial pressure of nitrogen in the nitrogen-argon mixture atmosphere as well, Fig. 1, Table 3. Increase of the partial pressure of nitrogen results in increasing of the width and penetration depth of the nitrated surface layers.

The highest microhardness of the nitrogen surface layer on substrate of titanium alloy up to 1300 HV0,2, ensures atmosphere of pure nitrogen and heat input 55 [J/mm], and alloying speed 1100 [mm/min], Fig. 4.

The highest resistance to erosion wear, but strongly dependent on the inclination angle of erodent stream, have the surface layers after laser alloying in nitrogen atmosphere at heat input 55 [J/mm], Fig. 5. The resistance to erosion wear at the inclination angle of erodent stream 90 [°], is about 18 [%] higher than the resistance of titanium alloy Ti6Al4V, and increases up to 3 times at the inclination angle 30 [°] Fig. 5.

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