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Diode laser gas nitriding of Ti6Al4V alloy

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ABSTRACT

Purpose: 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 produce titanium nitrides participations in the titanium alloy matrix surface layers.

Design/methodology/approach: Studies on influence of the parameters of laser gas nitriding of titanium alloy and partial pressure of nitrogen and argon in the gas mixture on the surface layers shape, penetration depth, microhardness, erosion wear resistance at different angles of erodent particles stream were conducted. The high power diode laser HPDL with a rectangular laser beam of even multimode intensity on the beam spot was applied in the laser gas nitriding process. Tests of erosion wear resistance were conducted according to the ASTM 76 standard at velocity of the erodent particles stream 70 [m/s], at angles 90 [°] and also 30 [°].

Findings: High quality surface layers of high hardness and erosion wear resistant were produced on the substrate of titanium alloy Ti6Al4V during Laser Gas Nitriding - LGN. Results of the study show that the erosion resistance of laser nitrided surface layers is significantly higher compared with the base material of titanium alloy Ti6Al4V, and depends strongly on the inclination angle of the erodent particles stream.

Research limitations/implications: Further investigations of internal stresses in the nitrided surface layers and the fatigue strength of extremely hard surface layers are required, because the fatigue strength is decisive for the functional quality of the surface layers.

Practical implications: The investigated technology of laser gas nitriding can be applied for increasing erosion wear resistance of surface layers of turbofan engine blades and steam turbine blades made of titanium alloy.

Originality/value: Application of the rectangular diode laser beam spot of multimode and uniform intensity of laser radiation is very profitable in a case of laser surface remelting and alloying because it guarantees uniform heating of the treated surface, consequently uniform thermal cycle across the area of the beam interaction and also uniform penetration depth of the single bead of the surface layer.

Keywords: Laser Surface Alloying; LSA; Laser Gas Nitriding; LGN; Titanium alloy

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

The titanium alloy Ti6Al4V is commonly used for manufacturing of rotors and fan blades of modern turbofan engines and rotors, blades of steam turbines of power plant generators [1-5]. Titanium and its alloys are favored because of its light weight, corrosion resistance and good high cycle fatigue properties but its erosion and cavitations resistance is not satisfactory [1-8]. 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 [9-15]. There are fallowing techniques of the laser surface alloying [9,10]:

- 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. 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 produce 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].

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 3. 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 2. 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. 1. 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, Figs. 1-5.

Table 1.
Chemical composition of titanium alloy Ti6Al4V

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.
Technical data of high power diode laser HPDL ROFIN SINAR DL 020

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 3.
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 and 2, Fig. 1 to 5

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. 1. 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 3.

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. 1,2,3. 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. 1,2,3, Table 3. 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]. 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 3. 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, Table 3.

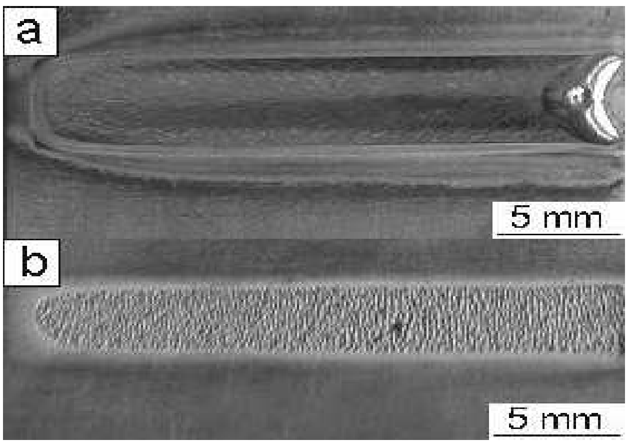

Fig. 1. A view of surface layers after laser alloying of titanium alloy Ti6Al4V in argon P1 (a), and nitrogen P5 (b) atmosphere with HPDL laser, Table 3

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. 4. 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. 4. 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. 4.

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 3.

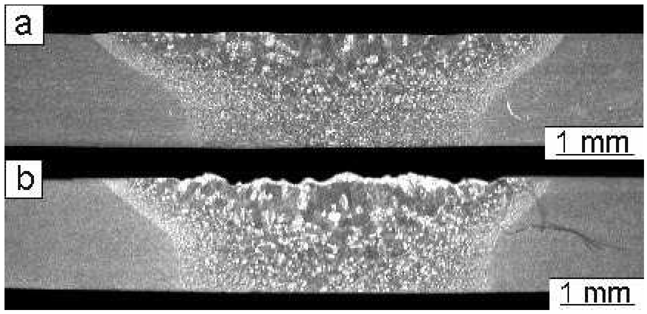

Fig. 2. Macrostructure of surface layers after HPDL laser alloying of titanium alloy Ti6Al4V in argon P1 (a) and nitrogen P5 (b) atmosphere, Table 3

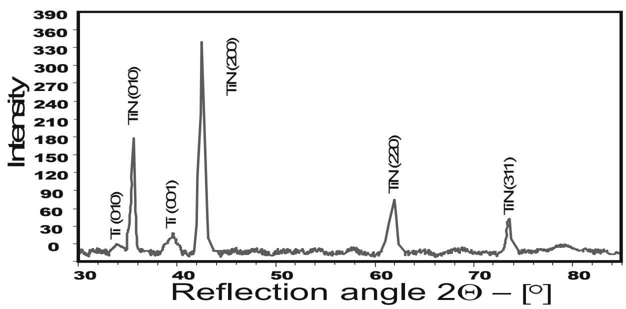

Fig. 3. XRD spectrum of the surface layer of titanium alloy after laser alloying in nitrogen P5, Table 3

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. 5. 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.

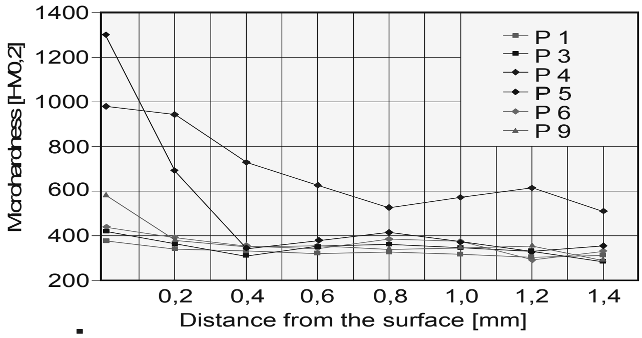

Fig. 4. Microhardness distribution on cross section of surface layer after HPDL laser alloying of titanium alloy Ti6Al4V in argon nitrogen mixture, Table 3

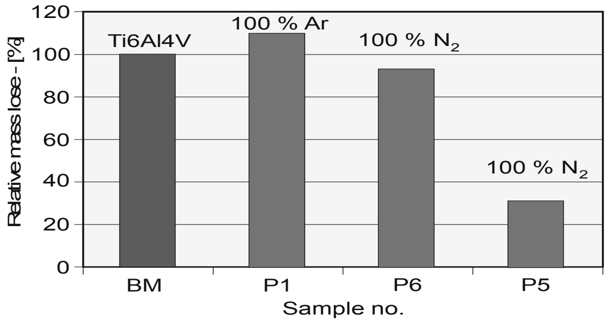

Fig. 5. Erosion wear resistance of the surface layers after laser alloying of titanium alloy in argon nitrogen mixture, at the inclination angle of erodent particles stream 30 [°], Table 3

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. 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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