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LASER SHOCK PEENING OF A Ti6Al4V TITANIUM ALLOY

LASEROWA ODKSZTALCAJĄCA OBRÓBKA POWIERZCHNIOWA STOPU TYTANU Ti6Al4V

The effect of the Laser Shock Peening (LSP) on the microstructure and properties of the surface layer of Ti6Al4V alloy has been studied. Laser shock processing was accomplished by a high-power Q-switched Nd:YAG laser, operating in a 1,064 μm wavelength range. The laser power density was 1 GW/cm^2 and a puls duration 18 ns. Before the laser processing the material was covered by a 50 μm absorption layer and 3 mm layer of water. Investigations of modified surface layer were carried out by scanning (SEM) and transmission electron microscopy (TEM). The chemical composition of treated surface was determined by Energy Dispersive Spectrometry (EDS), attached to the SEM. The mechanical properties (hardness and Young modulus) were determined by nanohardness measurements using a pyramidal Berkovich diamond nanoindentor. It was found that the LSP process was not purely mechanical but thermo-mechanical and lead to the formation of the surface layer composed of three well defined zones: external – oxidized with cracks and porosity, central zone - martensitic and internal – deformed, with high dislocation density level.

Keywords: laser shock peening, LSP, titanium alloy, surface layer, microstructure, hardness

W pracy przedstawiono wpływ laserowej obróbki odkształcającej na mikrostrukturę i własnosci warstwy wierzchniej stopu tytanu Ti6Al4V. Proces laserowego odkształcania przeprowadzono za pomocą lasera impulsowego o dużej gęstości mocy ReNOVALaser Nd:YAG z modulacją Q. Stosowano długość fali 1,064 μm. Gęstość mocy wynosiła 1 GW/cm^2, a czas trwania impulsu 18 ns. Przed procesem laserowego odkształcania powierzchnia stopu pokryta została absorpcyjną farbą o grubości 50 μm oraz warstwą wody o grubości 3 mm. Wpływ laserowej obróbki powierzchniowej na mikrostrukturę stopu Ti6Al4V zbadano za pomocą skaningowego (SEM) oraz transmisyjnego mikroskopu elektronowego (TEM). Analizę chemiczną wykonano za pomocą spektroskopii promieniowania rentgenowskiego z dyspersją energii (EDS). Własności mechaniczne (twardość i moduł Younga) zmierzono za pomocą nanotwardościomierza firmy CSM Instruments z wgłębnikiem Berkovicha. Wykazano, że przy tak dobranych parametrach laserowego odkształcania, proces LSP nie jest czysto mechaniczny ale termo-mechaniczny. Warstwa wierzchnia zbudowana jest z trzech stref: zewnętrznej – materiału przetopionego i utlenionego, charakteryzującego się porowatością i pęknięciami, środkowej strefy – martenzytycznej oraz wewnętrznej – materiału odkształconego, charakteryzującego się dużą gęstością dyslokacji.

1. Introduction

Titanium alloys are the most attractive metallic materials for aircraft, medicine and engineering industries due to their particular properties such as: low density, high strength to weight ratio, high corrosion resistance and good biocompatibility. At the same time, the disadvantages of titanium alloys are mostly their low wear and fatique resistance, as well as low hardness [1,2]. Therefore, numerous research groups have been trying to improve the properties of these alloys applying different surface treatments. One of the promissing method of improvement the titanium alloys properties seems to be the surface treatment by means of laser shock peening (LSP), which allow to introduce strain hardening and compressive residual stress into treated surface layer [3,4].

The principle of LSP is shown in Fig. 1. The LSP utilizes high energy short laser pulses that hit the surface of the material. When the power density of a laser pulse from a Qswitched laser is sufficiently high and when the short pulse hits a metal surface, shock waves can be generated. The shock waves propagating in the material create plastic deformation in the treated volume.

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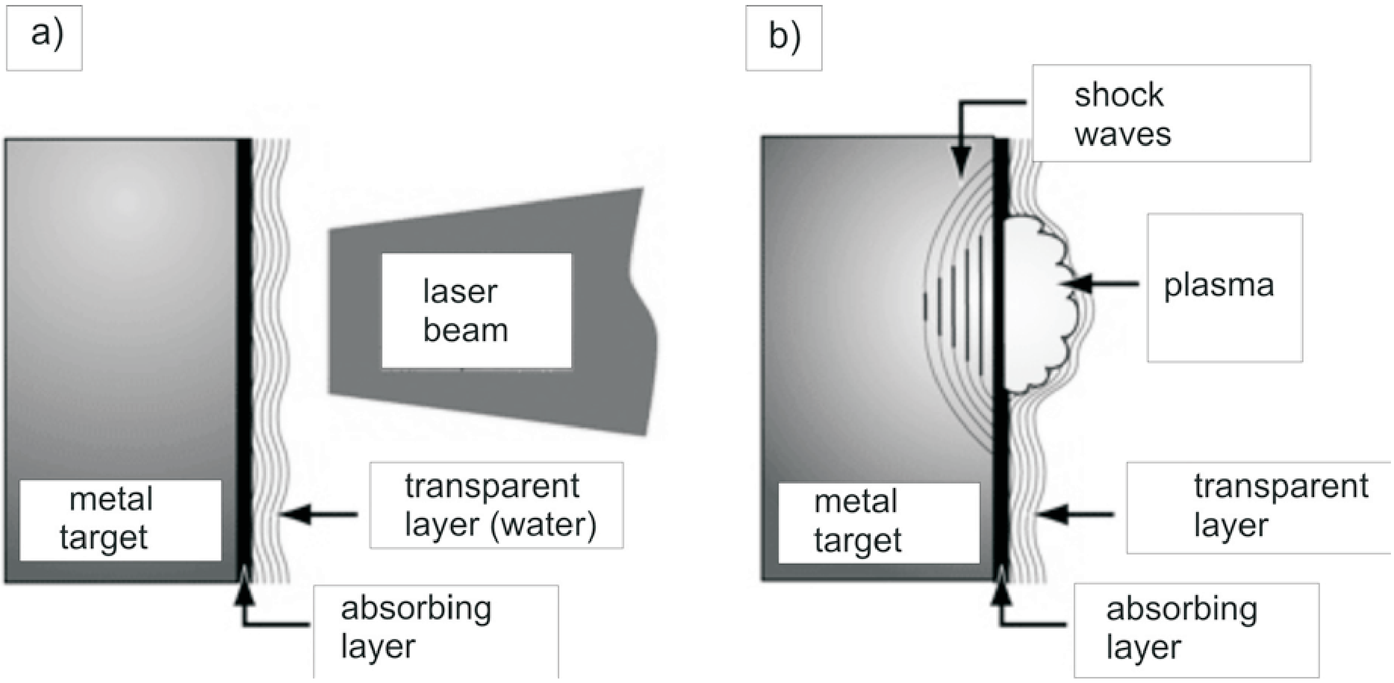

Fig. 1. Schematic representation of the laser shock peening (a) metal target with absorbing and transparent layers (b) shock wave generation by laser beam

Before laser shocking to be treated, surface of the material is usually coated with a black paint, as a laser-energy absorbing layer and covered with a transparent, inert layer (could be water, Fig. 1a). When the laser beam is directed onto the surface, it passes through the transparent layer and strikes the coated sample. The black coating, due to absorption of laser beam energy, is heated and instantaneously vaporized. The vapor absorbs the remaining laser beam radiation and produces plasma plume. The rapidly expanding plasma is trapped between the sample and the transparent layer (water), creating a high – surface pressure, which propagates into the material as a shock wave (Fig. 1b). If the surface of the material is enough protected from the temperature increase by an absorbing layer, the laser treatment becomes purely mechanical. When the shock wave generation occurs together with surface ablation, heating and melting of the treated material, the treatment becomes thermomechanical process [5].

The shock waves generated in the material can induce microstructural changes and cause high increase of dislocations density [6]. Indeed, the combined effect of microstructural changes and dislocations entanglement, contribute to an increase of the mechanical properties in the treated surface layer.

The aim of this work was to present the results of an investigation of the laser shot peening influence on the microstructure and properties of the Ti6Al4V titanium alloy.

2. Materials and experimental procedures

The investigated material was the Ti6Al4V alloy (Al – 6,1 %; V – 4,3 %; Fe – 0,17 %; C – 0,01; Ti – balance). Before the treatment the surface of the investigated material was ground and polished. Then, the treated surface of the material was coated with the 50 μm thick black paint, as a laser energy absorbing layer and covered with 3 mm thick layer of water (inert layer).

The laser shock processing was performed using a Q-switched Nd:YAG laser of 1 Joul energy, operating in the 1,064 μm wavelength range. The treatment was conducted in an air atmosphere. The laser shock processing was performed under the conditions of 1 GW/cm^2 laser power density and a puls duration of 18 ns. During the laser shot processing the central part of the disk shape sample (16 mm of diameter) has been treated (series of overlapping spots – 5 subsequent laser shots to the same spot), covered the rectangular 10 mm × 5 mm area, as shown in Fig. 2. After LSP, the remaining black paint coating was stripped off with the acetone.

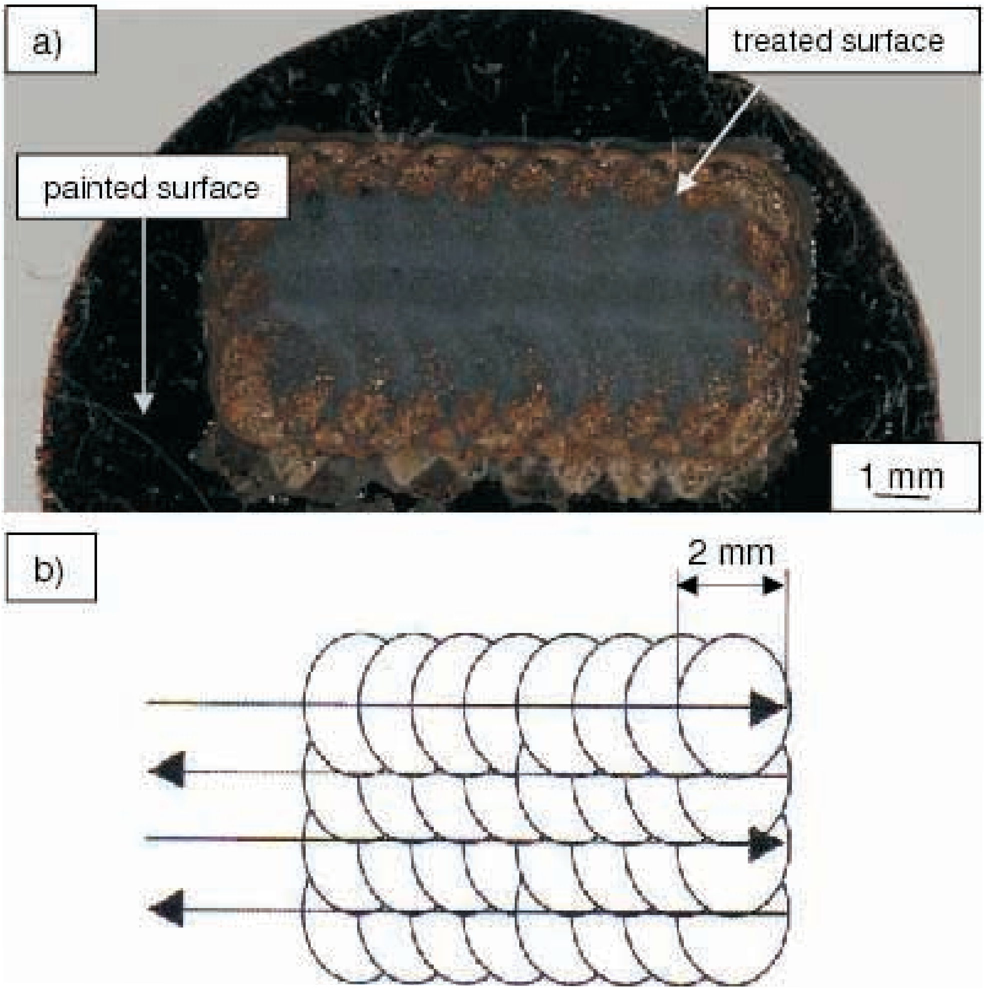

Fig. 2. Optical image showing the treated sample (a) and scheme of the treated area (b)

Specimen preparation for microstructural evaluation was carried out using standard metallographic techniques. Scanning electron microscopy (SEM, Hitachi S – 3500 N) was performed on the laser treated surfaces, as well as on the cross sections of the treated sample. The chemical composition of treated surface was determined by means of Energy Dispersive Spectrometry (EDS, Noran 986B – 1SPS), attached to the SEM. Detailed microstructural investigation of modified surface layer was carried out by Transmission Electron Microscopy (TEM, Philips CM20). Thin foils were cut perpendicular to the treated surface and prepared using FEI focused ion beam (FIB) Quanta 3d system. The mechanical properties (hardness and Young's modulus) were determined by nanohardness measurements (CSM Instruments equipment) using a pyramidal Berkovich diamond nanoindentor with a 300 mN load.

3. Results and discussion

Morphological changes of the Ti6Al4V titanium alloy surface after laser treatment are presented in Fig. 3. SEM images of the treated surface show that laser shock peening caused an ablation and melting of surface layer of alloy. The rapid heating and melting accompanied with a high pressure of plasma caused that the liquid metal spilled from the central part of the treated area towards the periphery (Fig. 3. a), where, due to an intensive cooling, has been frozen. As a consequence the roughness of the surface increased. The surface roughness was in addition increased by an effect of overlapping of subsequent treated areas. Presence of droplets on the surface indicates that the process of the laser shock peening was not purely mechanical but rather a thermo-mechanical. After several (5) laser beam shots, the central part of the treated surface was damaged and cracked (Fig. 3. b). SEM images of the treated sample cross sections showed that the cracks propagate perpendicular to the heated surface (Fig. 4) but only through the very thin melted zone (1 – 4 μm thick).

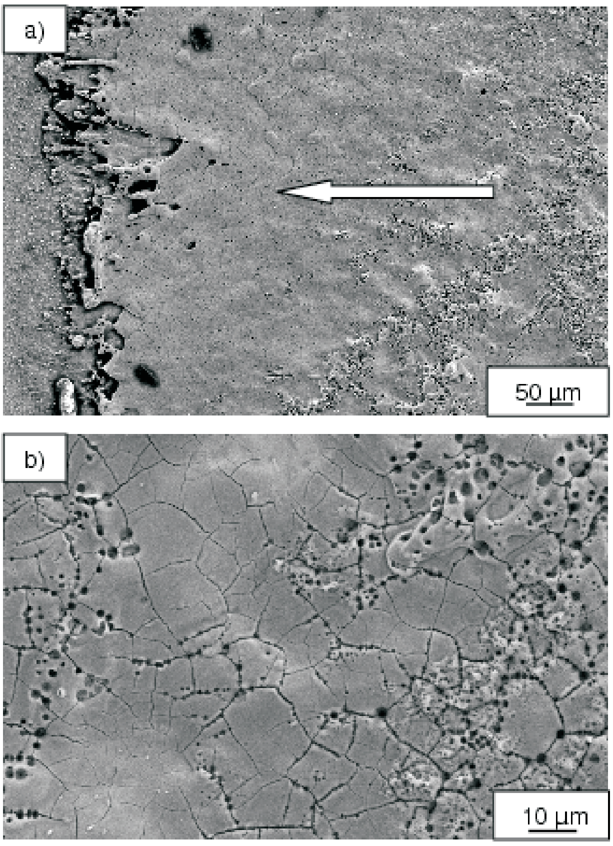

Fig. 3. SEM images of the surface after laser shock peening; (a) — periphery, arrow indicates direction of the molten material flow and (b) – the central part of the treated area

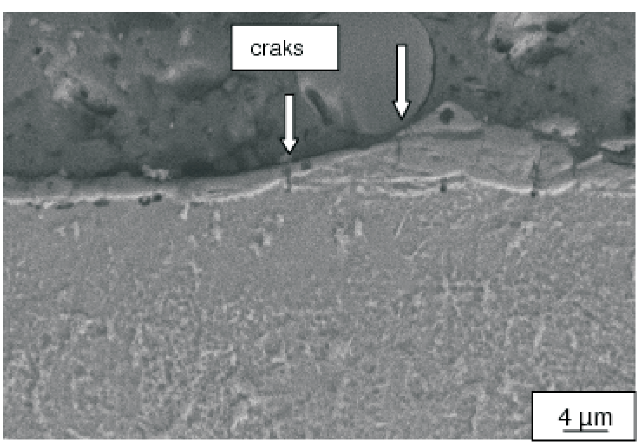

Fig. 4. SEM micrograph of the sample cross-section after laser shock processing; arrows indicate presence of cracks in the melted zone

Chemical analysis of the treated surface indicated presence of titanium and aluminum, as well as oxygen (Fig. 5) in the melted zone. It indicates possible alloy oxidation during laser processing. Oxidation may occurred due to the water layer vaporization and absorption of oxygen by a molten material. All elements present in the treated material, specifically Ti and Al have high efficiency to oxygen.

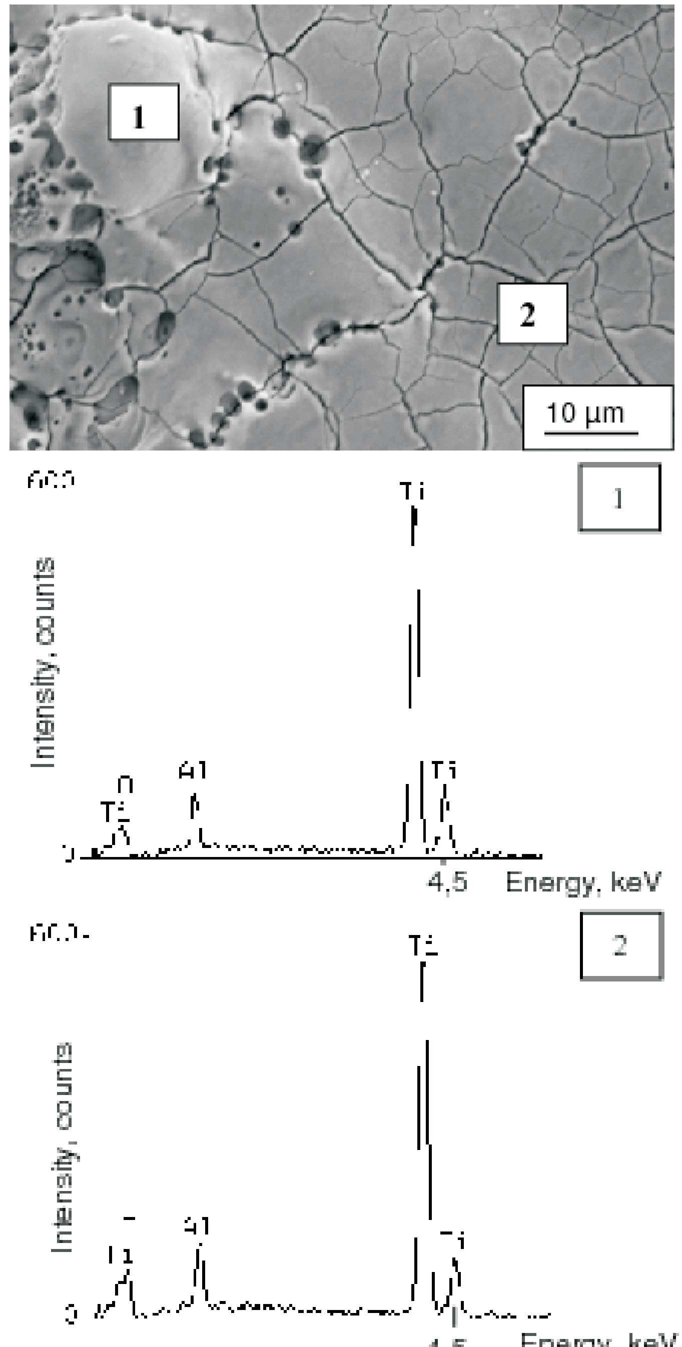

Fig. 5. The EDS spectrograms show presence of oxygen, titanium and aluminum at the alloy surface

Typical TEM microstructure of the Ti6Al4V titanium alloy after laser shock peening is shown in Fig. 6a. The Transmission Electron Microscopy observations of the thin foils showed that LSP process resulted in formation of the surface layer composed of three well defined zones: external – oxidized with cracks and porosity, central zone - martensitic and internal - deformed, with high dislocation density level. External, melted and oxidized zone shows high porosity level (see images: SEM in Fig. 3 and TEM in Fig. 6b), and ultrafine, grained microstructure of nanometric scale. Appearance of porosity at the treated surface is probably due to the ablation of the material occurring during the laser processing. The thickness of the second martensitic zone varied between 1-2 μm. During laser processing, the material in this zone was heated up to the temperature range where β phase is present in Ti6Al4V alloy. Due to the rapid cooling, after laser processing β phase transformed to the α' martensite phase. One must remember that such heating/cooling cycle was repeated 5 times in the same area. Indeed, such treatment induced strong grain refinement resulting in ultrafine martensitic structure in that zone. The third zone – of the deformed material contains larger, of a few μm in diameter, grains with high dislocation density and slip bends.

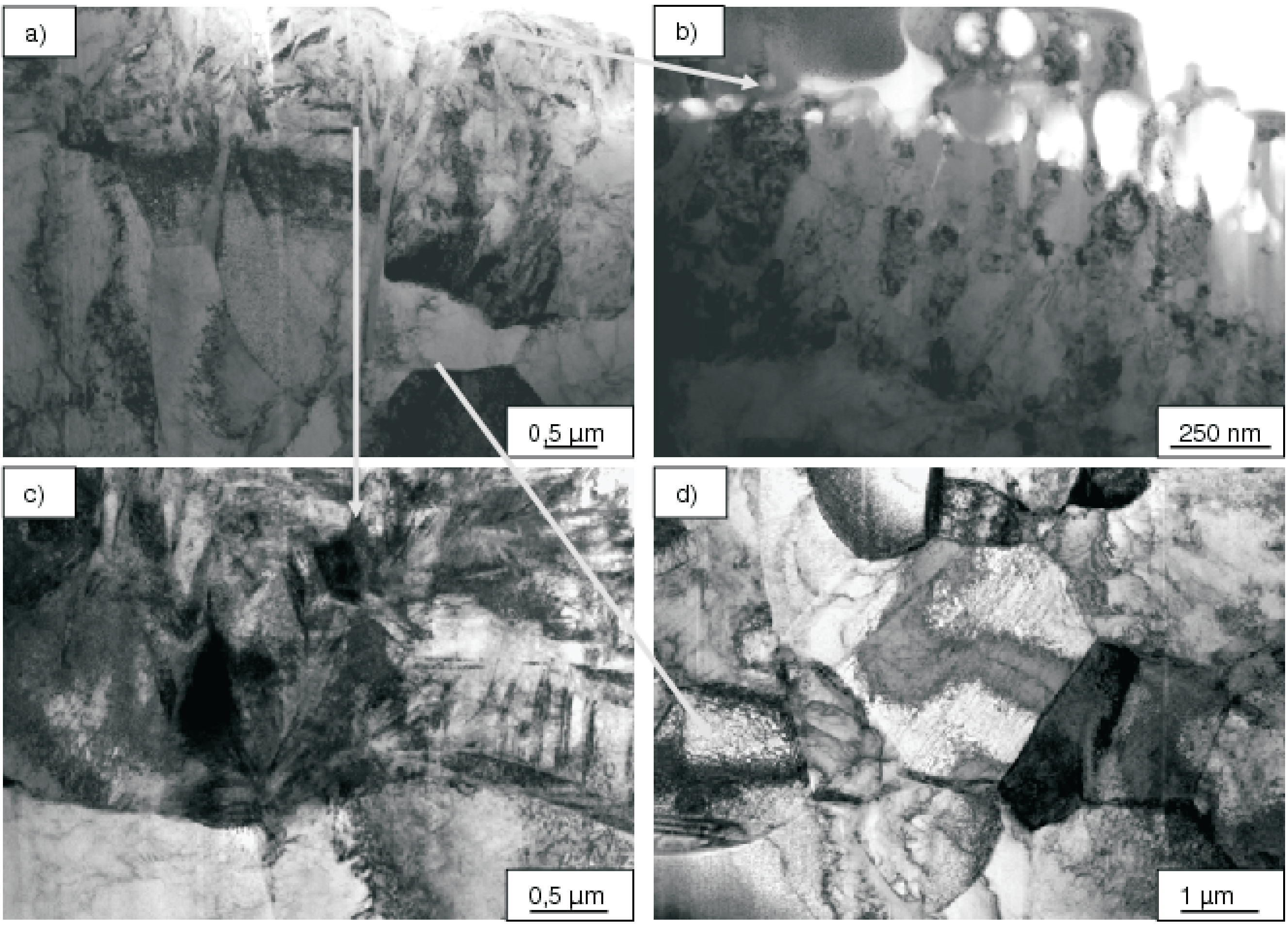

Fig. 6. Typical TEM microstructure (a) of the Ti6Al4V titanium alloy after laser shock peening composed of three zones: (b) -external – oxidized with cracks and porosity, (c) – central martensitic and (d) — internal, deformed, with high dislocation density level and slip bends

The nanohardness values measured on the polished cross-sections showed that the hardness of the layer contained martensite and a high density of dislocations (approximately up to 0,5 mm) was much higher (varied between 360 – 480 nHV) than that of the matrix (290 nHV). Also the Young's modulus values of the investigated internal deformed surface layer (140 GPa) and was slightly higher than that of the matrix (127 GPa).

4. Conclusions

- It was found that the laser shock processing performed under the conditions of 1 GW/cm^2 laser power density and puls duration of 18 ns caused an ablation and melting of the surface layer of the treated material, what indicated that the process of the laser shock peening was not purely mechanical but rather thermo-mechanical.
- TEM observations showed that laser shock peening resulted in formation of the surface layer composed of three well defined zones: external oxidized with

cracks and porosity, central martensitic and internal deformed, of high dislocation density level.

- Martensitic $\beta \rightarrow \alpha'$ transformation and increased dislocation density seems to be the main sources that harden material during LSP process and result in an improvement of its mechanical properties.

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