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MECHANICAL PROPERTIES OF TITANIUM GRADE 1 AFTER LASER SHOCK WAVE TREATMENT

ABSTRACT

In the presented work the impact of a laser shock wave on the mechanical properties of a Titanium Grade 1 was investigated. Based on a series of experimental studies related to the impact of the laser shock wave on the tested material, the impact of the given treatment on the structure and mechanical properties was assessed. The influence of the environment on the distribution of plasma temperature and pressure in the material during the implementation of the laser shock wave was analyzed. The effect of the laser treatment on the structure and micromechanical properties was initially estimated on the basis of the analysis of experimental results in the form of static strength test of samples after laser treatment. A slight increase in material strength was detected with a minimal decrease in ductility. In order to comprehensively understand the observed phenomenon, a number of fractographic tests were performed, especially the analysis of the porosity of the fracture surfaces. A decrease in the porosity of the material after impact laser treatment was observed as a result of local plastic deformation.

Keywords: *Titanium grade 1; mechanical properties; laser shock wave; monotonic stretching; porosity*

INTRODUCTION

Laser shockwave treatment is a technologically advanced method of material processing. This technology makes it possible to change the structure and properties of materials at depths far exceeding the depth of the thermal laser pulse [1-3]. Considering the large number of modern materials and the difficulty of modelling the processes occurring during laser processing, it is important to conduct experimental studies in order to analyses the structure

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and properties of the irradiated materials [4-7]. In recent years, many studies have been conducted on laser shockwave treatment of titanium and titanium alloys. Nowadays, titanium is a material used in almost all fields: mechanical engineering, aerospace, medicine, etc. It is interesting to study titanium after shock wave laser treatment with high-power lasers to obtain unique local physical and mechanical properties [8-10]. In the article [11], the structure and properties of the Ti-17 titanium alloy after laser treatment with a shock wave in water using the Nd: YAG laser were investigated. The pulse energy was 85 mJ, the wavelength was 532 nm, the pulse duration was 10 ns, and the spot diameter was 400 μm. It was shown that after treatment, the fatigue strength of the material increased from 390 to 475.4-490.3 MPa. An additional residual stress (-456.1 MPa) was introduced on the surface. The microstructure and fractograms were studied by electron microscopy. It has been shown that the dislocation density in the material after treatment increases. In [12], changes in Ti-17 titanium after Nd: glass laser treatment with a thermal protective coating in water were studied. The pulse energy was 5 J, wavelength 1064 nm, pulse duration 10 ns, spot diameter 3 mm. After treatment, there was an almost 3-fold increase in the residual comparative stress compared to the base material. The examination of the fractograms of the samples after the impact and surface microstructure tests using electron microscopy showed a reduction in the number of grains and an increase in the number of dislocations, which led to an improvement in impact strength. The average impact energy increased by 10 J. In [13], the mechanical properties of the Ti-13Nb-13Zr titanium alloy after laser treatment with the Nd: YAG laser in water using a black protective tape were studies. The pulse energy was 6 J, wavelength 1064 nm, pulse duration 15 ns, spot diameter 3 mm. Residual stress on the surface has been shown to increase by 5-7 times depending on the number of laser shots. The surface roughness increases, which is associated with plastic deformation after machining. The surface microhardness after laser treatment increases from 330 to 370-390 HV. It was also shown that the improvement in properties is associated with a reduction in the size of the alloy grain. In [14], the impact of laser treatment with shock wave in water using the Nd:YAG laser on the surface of aluminium and titanium alloys was studied. The pulse energy was 2 J, wavelength 1064 nm, spot diameter 1.5 mm, pulse duration – several ns. The change in relief and surface structure is shown. Machining leads to an increase in residual stress, as well as an increase in the wear resistance of the material. The impact of laser treatment with a shock wave on the mechanical properties of titanium alloys was studied in [15]. A Nd: YAG laser with a wavelength of 532 nm, pulse duration of 8 ns, pulse energy of 50 mJ and spot diameter of 0.4 mm was used. It has been shown that laser treatment leads to an increase in the fatigue strength of the material and an increase in residual stress. The TC6 titanium alloy was tested after Nd: YAG laser treatment in water with a thermal protective coating in work [16]. The pulse energy was up to 10 J, the radiation wavelength was 1064 nm, the pulse duration was 18-20 ns, the spot diameter was 2.6 mm. It was shown that the fatigue strength of the material was improved. The analysis of the microstructure and fractograms using electron microscopy showed grain refinement and a change in the direction of crack propagation in the material. It has been shown that after treatment, the residual stress increases to 600 MPa, and the microhardness increases to 421.5 HV, which is 18.7% more than in the starting material. The effect of laser treatment on pure titanium has been studied in [17]. Nd: YAG laser was used for processing, radiation wavelength 532 nm, pulse duration 7 ns, spot diameter 3 mm, laser radiation intensity - 9.1 GW/cm^2. The oxidation behaviour of titanium has been shown to improve after laser treatment. There is an increase in microhardness and the appearance of a large number of twins after laser shockwave treatment. In the last few years, research has begun on the problem of generating structural defects in matter under the influence of short pulses of laser radiation. The energy intensity in such experiments usually does not exceed 10^9 W/cm^2, so as

to avoid causing noticeable thermal effects at a depth greater than $\sqrt{\alpha\tau}$, where α is the heat transfer coefficient, within a few tens of nanoseconds. Under these irradiation conditions, a shock wave is generated near the surface of the sample, the front propagation of which changes the properties of the material [18, 19]. In experiments with a laser shockwave, which differs from other methods of generating shockwaves, it is fundamentally simplified to obtain the shape of the wavefront – flat, cylindrical, spherical, as well as the number of shock pulses, since the first of them depends only on the shape of the absorbing surface, and the second one on the selection and adjustment of the optical emitter and modulator of the Q factor [20-22]. Nanosecond laser treatment of titanium has found its application in medicine and dentistry. Such processing allows to improve not only the mechanical properties, but also the biocompatibility of titanium implants [23-25].

The set of phenomena occurring in materials irradiated with nanosecond laser radiation is still not well understood, despite many publications on particular topics and attempts to create integral theories, focused primarily on the study of the impact of laser shock waves on the formation of defects and mechanical properties of materials [26, 27]. This is most important for determining the mechanisms of laser shockwave energy dissipation and resulting defects and is important not only for modifying the properties of materials, but also for studying their behaviour under high-velocity loads. The aim of this article is an attempt to develop a methodology for conducting a preliminary assessment of the impact of a laser shock wave on modifying the mechanical properties of a titanium Grade 1.

MATERIALS AND METHODS

The impact of the laser shock wave on the modification of mechanical properties was tested on the titanium Grade 1. The chemical composition and mechanical properties of the original material are presented in Table 1.

Table 1. *Chemical composition and mechanical properties of the Titanium Grade 1*

Indication according to standards		Elemental content, [weight %]						Mechanical properties according to standards		
ASME	UNS	Fe	O	N	C	H	Ti	R_m [MPa]	$R_{0,2}$ [MPa]	A5 [%]
SB-265 Grade1	R50250									
Elemental content according to standards		Max 0.20	Max 0.18	Max 0.03	Max 0.08	Max 0.015	balance	≥ 240	138-310	28
Elemental content according to material delivery companies		0.022	0.047	0.005	0.004	0.003	balance			

For the tests, a 2 mm thick titanium sheet was used, from which, after laser treatment, samples for testing under monotonic stretching conditions were cut out. A pulsed Nd: glass laser in the Q-switch mode was used to process the samples. Laser wavelength - 1060 nm;

laser pulse duration - 50 ns; laser spot diameter – 3 mm; energy flux density - 1-1.5×10^9 W/cm^2. The overlap of the laser spots during exposure was about 10%. Laser processing was carried out in air and in a transparent condensed medium in the quality of which the resin was used. The transparent condensed medium limits plasma expansion and increases the pressure of the laser shock wave on the sample. The laser shockwave is a pressure surge in the irradiated material, which propagates in it at supersonic speed. The laser shockwave is therefore the main factor changing the structure and properties of the material during nanosecond laser processing. The general diagram of the test stand for laser processing of materials is shown in Fig. 1, while Fig. 2 shows the diagram of impact laser processing using a condensed transparent medium.

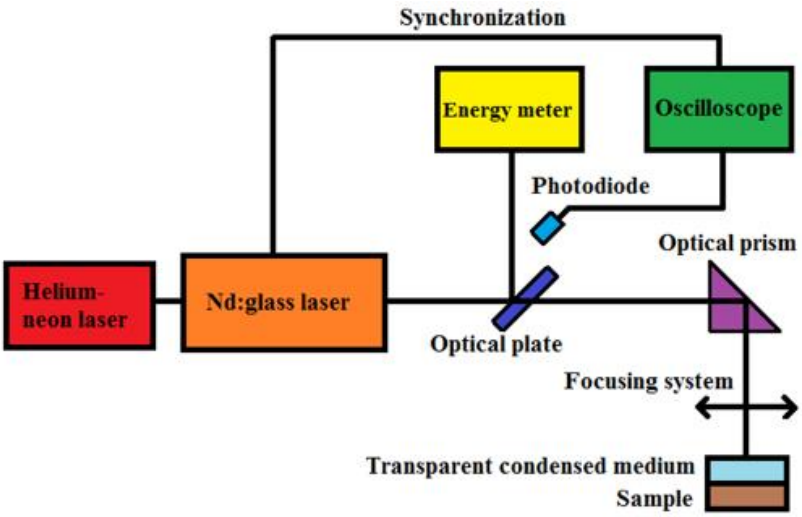


Fig. 1. General scheme of the test stand for laser processing of materials

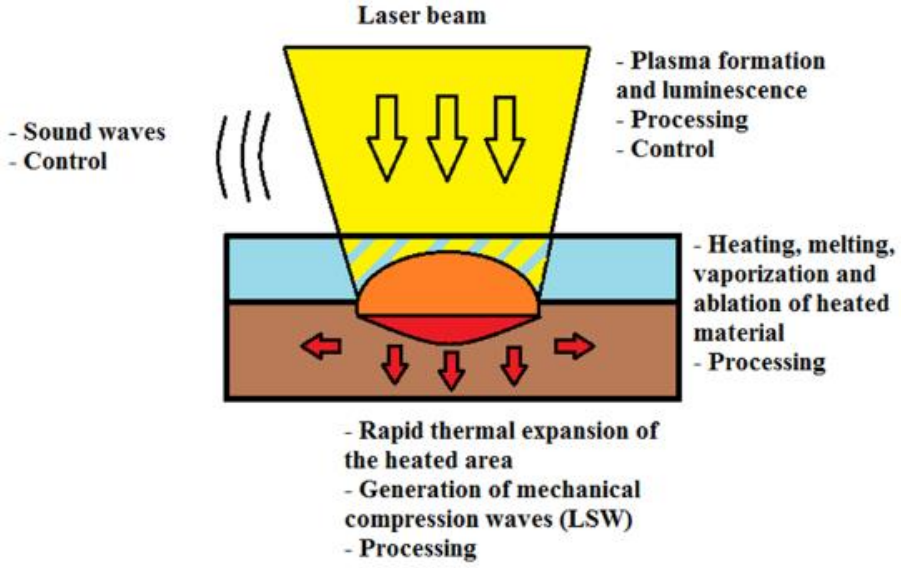


Fig. 2. Treatment of materials with a laser shockwave

The laser shockwave processing was carried out on both sides of the sample according to the exposure scheme shown in Fig. 3.

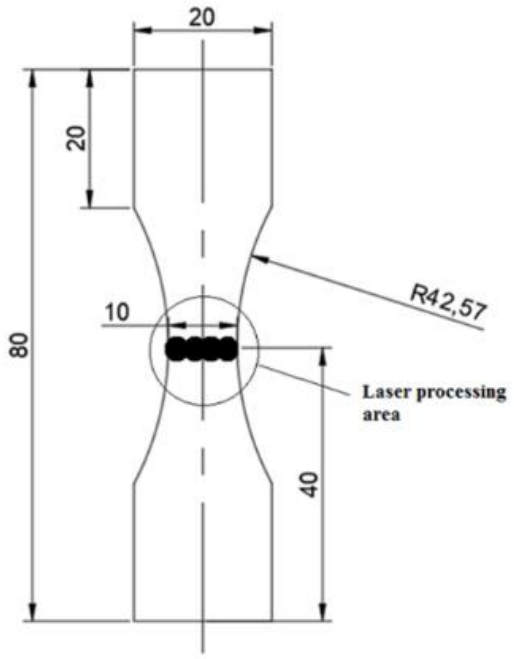


Fig. 3. Scheme of laser irradiation of samples

The samples for testing under monotonic stretching conditions were cut using a wire EDM machine. In order to locate the area of sample destruction, it was decided to make hourglass-shaped samples. The tests of mechanical properties were carried out on the universal testing machine Instron 8802 with the registration of displacement and strain using a strain gauge and the DIC system.

Fractographic tests carried out using SEM JEOL JSM-6610. Porosity studies were carried out using the image analysis method based on a proprietary algorithm developed in-house. The image analysis algorithm is matrix-based, i.e. we consider images obtained in secondary electron mode (SEI) characterized by gray scale of the recorded photos as an m by n matrix, where m and n are the width and height of the image in pixels, and the number is the shade of grey (from 0 to 255 shades, where 0 is the blackest color and 255 is the whitest).

An empirical elemental analysis of the image is then performed and it is concluded that since titanium is a porous material, the pores in the image have a shade of 0 to 55 (black) and anything above 55 (i.e. from 56 to 255) is the base material.

This converts a grey image to a binary (black and white) image where all shades up to 55 are equal 0, and shades from 56 to 255 are equal 1. Then we can calculate the number of black pixels in the resulting image, i.e. find the area pore size and compare the pore areas of the original material and the laser impact treated material.

RESULTS AND DISCUSSION

Calculation of the temperature field

Calculations of the temperature field during laser shockwave treatment are based on solving the thermal conductivity equation.

$$T(z,t) = \frac{2q\sqrt{at}}{\lambda} ierfc(\frac{z}{2\sqrt{at}}), \tag{1}$$

One solution to the thermal conductivity equation for a rectangular shape of a laser pulse is the formula:

where:

ierfc (u) – probability integral function;
λ – thermal conductivity;
q – energy flux density;
a – coefficient of thermal conductivity of the material;
z – depth of the heated layer;
t – laser pulse duration.

In contrast, with laser shockwave treatment, the laser pulse is triangular or trapezoidal. The temperature distribution in the sample during treatment with a nanosecond laser pulse is as follows:

$$T(r,t) = \frac{q\sqrt{a}}{\lambda\tau_i}(4t)^{3/2} i^3 erfc\frac{z}{2\sqrt{at}} \tag{2}$$

Using the theory of fictitious sources, the equation for the temperature distribution under the action of a triangle pulse is as follows:

$$T(r,t) = \frac{q\sqrt{a}}{\lambda\tau_i}\left[(4t)^{3/2} i^3 erfc\frac{z}{2\sqrt{a\tau}} - 2(4(t-\tau))^{3/2} i^3 erfc\frac{z}{2\sqrt{a(t-\tau)}}\right] \tag{3}$$

Laser processing using a transparent condensed medium is complicated by the fact that some of the energy is diverted to the POS due to heat transfer, and after the end of the laser pulse, the plasma becomes the energy source. Then the solution to the equation will be as follows:

$$T(z,t) = \frac{2q\sqrt{at}}{\lambda} ierfc(\frac{z}{2\sqrt{at}}) \tag{4}$$

Square pulse duration:

$$\tau = \frac{2l}{c}$$

where:

l – POS thickness,
c – speed of sound propagation in a particular POS.

Fig. 4 shows the temperature distribution in the titanium sample during the laser pulse, which shows that the thickness of the plasma formed during the laser pulse is 4 to 5 μm with energy ranging from 30 to 60 J/cm^2.

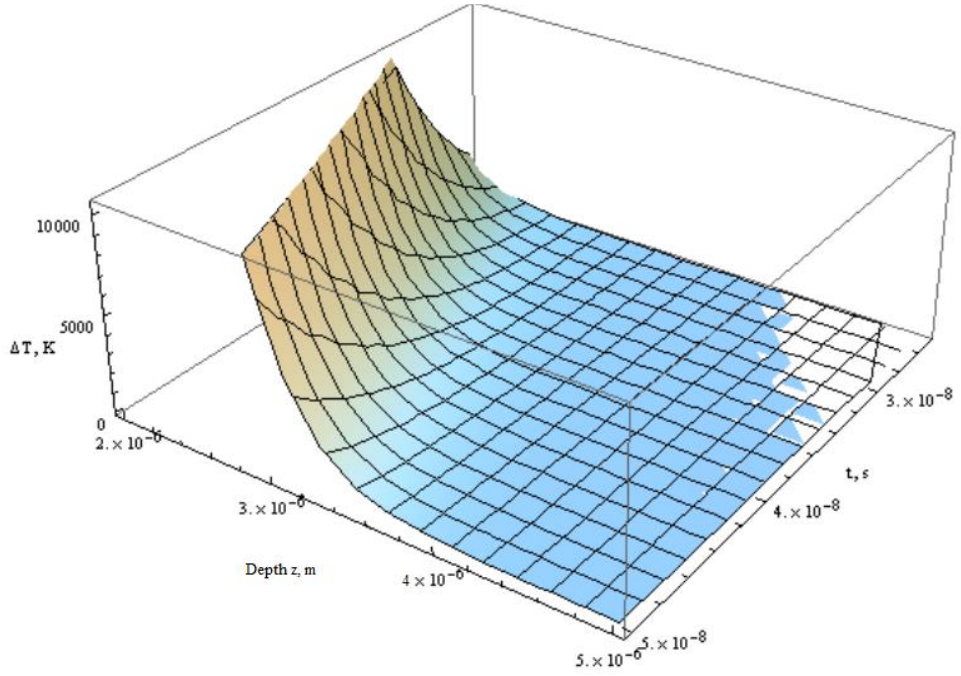


Fig. 4. Temperature distribution in titanium during irradiation in epoxy resin. (x axe: Depth z, [m]; y axe: t, [s]; z axe: ΔT, [K])

After the end of the pulse at the depth z, where the temperature is higher than the boiling point of the material, the contact between the surface and the evaporated layer is broken. The energy source in this case can be considered instantaneous. Therefore, we need to switch to a new coordinate system in which the formula for the temperature distribution will be:

$$T = \frac{T_0 x^2}{(t + \frac{x^2}{2a})2a} e^{-\frac{z^2}{4a(t+\frac{x^2}{2a})}} \tag{5}$$

The pressure occurring during the irradiation of samples in air can be estimated by the equation:

$$P_{pl} = (a_{pl}t)^{-1/3} I^{3/4} \tag{6}$$

where:

α_{pl} - coefficient characterizing plasma properties;

t – laser pulse duration;

I – intensity of laser radiation.

In order to increase the pressure of the shock waves, a special laser treatment technique was developed in a transparent condensed medium (POS) using a copper shield. The formula for calculating the pressure amplitude during laser processing using a transparent condensed medium is:

$$p = \sqrt{q\frac{\gamma - 1}{\gamma} \cdot \frac{\rho_1 D_1 \cdot \rho_2 D_2}{\rho_1 D_1 + \rho_2 D_2}} \tag{7}$$

where:

ρ_1, ρ_2 – densities of unexcited centers 1 and 2;
D_1, D_2 - propagation velocities of the compensation wavefront;
γ - adiabat power indicator, which is equal to 5/3 for monatomic gas, 7/5 for diatomic gas and 9/7 for triatomic gas and more.

This formula allows us to accurately determine the pressure on the surface of a sample when it is irradiated by a transparent condensed medium. Thermal insulation coatings can be aluminium, zinc, copper and organic coatings. It should be noted that black paint is the most practical compared to other coatings. It is easy to apply and provides reliable acoustic contact with the surface. The thickness of the absorbent coating should be greater than the depth of heat penetration into the material to protect the surface from thermal effects. Figures 5 and 6 show the graphs of plasma pressure during irradiation in air and in POS as a function of the energy density of the laser pulse, calculated on the basis of formulas 6 and 7. As can be seen from the graphs, the plasma pressure during irradiation in POS is an order of magnitude higher than the plasma pressure during air irradiation.

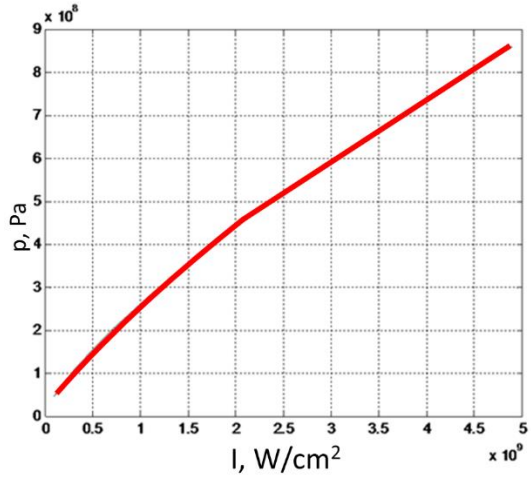


Fig. 5. Graph of plasma pressure versus flux density during air irradiation

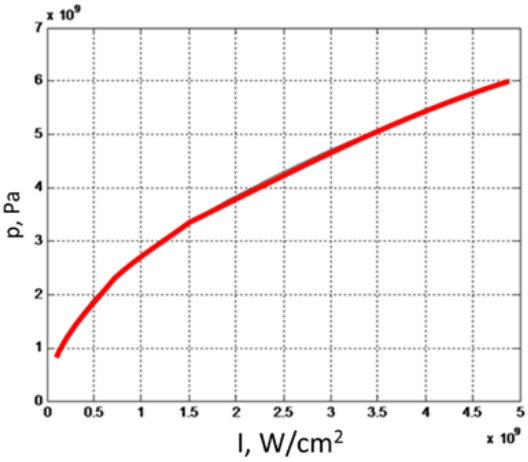


Fig. 6. Plot of plasma pressure versus flux density during irradiation in PCS

For practical tasks, the following formula is much more convenient than formula (7):

$$p = \frac{2}{d}\sqrt{\frac{E}{\pi\tau_i}\frac{\gamma - 1}{\gamma} \cdot \frac{\rho_1 D_1 \cdot \rho_2 D_2}{\rho_1 D_1 + \rho_2 D_2}\left[\frac{\Delta F}{2F} + H\left(\frac{1}{2F} - \frac{1}{\sqrt{n^2(4F^2 + d^2) - d^2}}\right)\right]^{-1}} \tag{8}$$

where:

F – focal length of the lens;
ΔF - defocus (distance from the focus of the lens to the surface of the material);
d - diameter of the cylindrical lens;
n - refractive index of a transparent condensed medium;
H - layer thickness of a transparent condensed medium.

Evaluation of Ti Grade 1 porosity modification by computer image analysis

Two images of fractograms of the original material and two images of fractograms of the treated material obtained in the same places of the sample with the same resolution were selected for the analysis (Fig. 7 and Fig. 8). The number of black pixels in absolute and relative terms (i.e. the ratio of the number of black pixels to the total number of pixels) and the number of black pixels to the total number of pixels in the image are also shown. This method is a good way to automate image analysis, which gives both a qualitative and quantitative image.



The number of pixels in absolute terms is 83927
The number of pixels in relative values 1.8712%
in the initial state



The number of pixels in absolute terms is 76381
The number of pixels in relative values 1.7030%
after laser processing

Fig. 7. Analysis of the porosity of the tested material (position I)

The ratio of the number of pixels after analysis to the number of pixels before the analysis is 91.0089%. The number of pores decreased by about 9%.



The number of pixels in absolute terms is 188024
The number of pixels in relative values 4.1922%
in the initial state



The number of pixels in absolute terms is 87360
The number of pixels in relative values 1.9478%
after laser processing

Fig. 8. Analysis of the porosity of the tested material (position II)

It can be seen that the number of pores after laser shockwave treatment decreased compared to the original material. This means that the pores are closed during the passage of the shock wave in the material, which means that plastic deformation can be one of the factors increasing strength after laser treatment. The average test results of the samples in the conditions of monotonic stretching of the base material and after laser impact treatment are shown in Fig. 9.

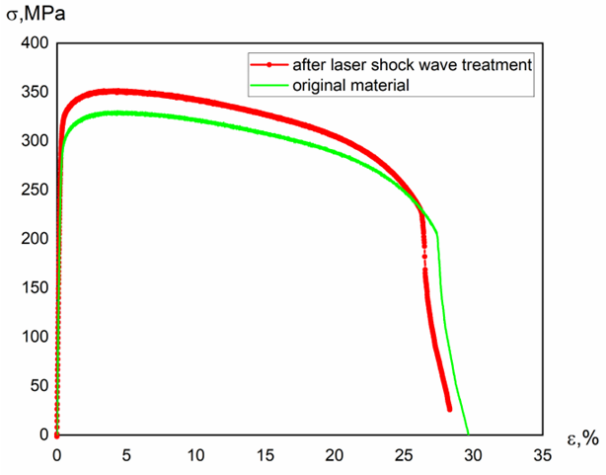


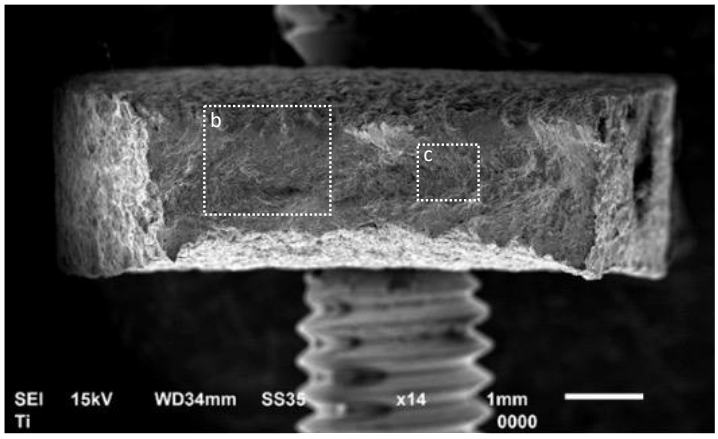
Fig. 9. Results of the titanium grade 1 tensile test in states before and after shock wave treatment

As can be seen from the graphs presented in this figure, the minimum width of the sample surface (a band with a width of about 3 mm) clearly changes the macro-mechanical properties of the tested material. An increase in stress in the samples after laser impact treatment is noticeable, followed by a minimal decrease in the plasticity of the material. It is worth noting that due to the large dispersion of the initial values of the yield strength and strength of the material in the initial state, the obtained values are not very speculative and do not give strong conviction for the practical use of the tested method of material processing. Nevertheless, it is crucial to visualize the trend of increase (change) of the material's macro-mechanical properties. Therefore, it seems reasonable to conduct a number of further studies related in particular to the microstructural analysis of the material in order to identify structural changes caused by laser treatment, as well as low- and high-cycle tests to verify the behaviour of the material in conditions similar to operating conditions. Then, taking into account also the modifications of the parameters of impact laser treatment, it will be possible to determine the complex effect of the proposed laser treatment on the mechanical properties of the tested alloy.

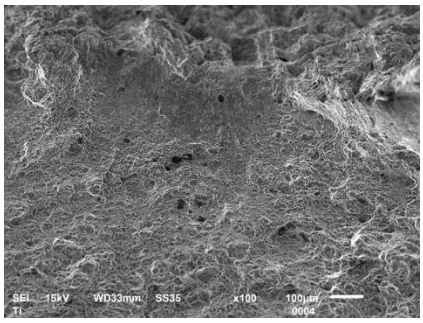
Observations of fracture surfaces were carried out to assess the influence of laser shock wave treatment on the mechanism of crack propagation. Fractography observation performed using SEM in secondary electron mode shows the fracture surface of titanium in samples in base state before treatment (Fig. 10) and subjected to laser shock wave treatment (Fig. 11). Results for the samples before treatment revealed typical fracture surface to titanium Grade 1. That the initiation of the crack is observed at the edge of the sample and is characterized by the brittle area what is shown in Fig. 10a,b. Fracture surface further from the initiation zone is characterized by the plastic fracture (Fig. 10c). Interesting results were obtained during examination of the surface of the samples subjected to the laser shock wave treatment. The crack initiation was started from both edges of the sample what was observed by the brittle character of fracture in the distance about 327 and 218 μm from the edges (Fig. 11a,b). Brittle

fracture, in accordance with the sample before treatment, was observed along the edges of the sample what can be correlated with area of hardening after the treatment. Fracture surface further from the initiation areas is characterized by the plastic fracture (Fig. 11c).

a)



b)



c)

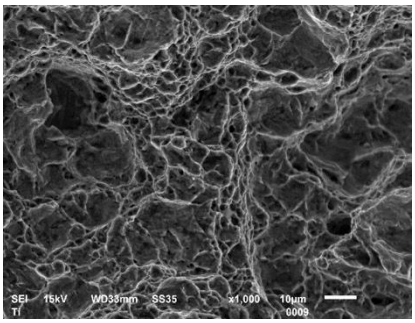
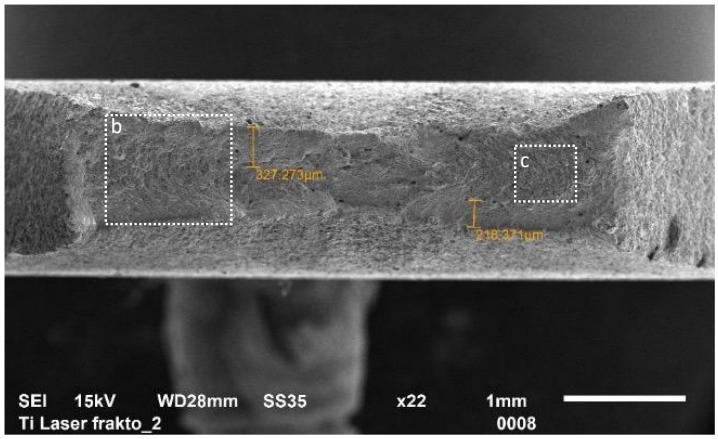
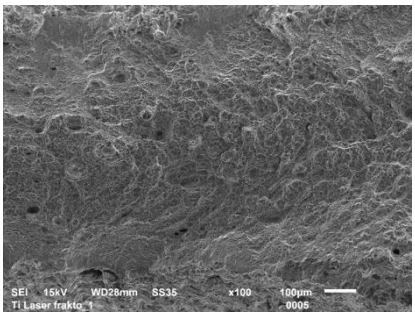


Fig. 10. Fractography observation results for sample in initial state

a)



b)



c)

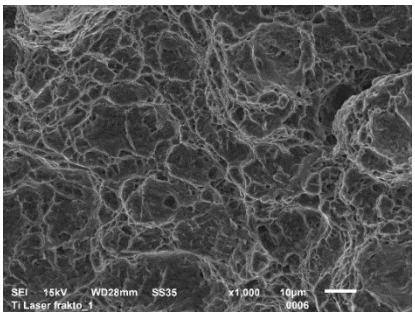


Fig. 11. Fractography observation results for sample in state after laser shock wave treatment

CONCLUSIONS

The following conclusions can be drawn from the completed study:

- For samples after laser impact treatment, an increase in stress is observed, followed by a minimal decrease in plasticity of the material. It is worth noting that due to the high variability of the initial values of the yield strength and strength of the material in the initial state, the obtained values are not speculative in nature.
- It was found that the number of pores after laser shockwave treatment decreased compared to the starting material. This means that closing the pores during the propagation of the shock wave in the material, which induces plastic deformation, may be one of the factors increasing the strength after machining.
- The plasma pressure during irradiation in a transparent condensed medium is an order of magnitude higher than the plasma pressure during irradiation.
- It is interesting to conduct further studies with the aim of applying laser shock wave treatment in order to change the structure and properties of finished products made of titanium, which are used in medicine and the aerospace industry

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REFERENCES

1. Montross C.S., Wei T., Ye L., Clark G., Mai Y-W.: Laser shock processing and its effects on microstructure and properties of metal alloys: a review. International Journal of Fatigue 24 (2002), 1021-1036.
2. Boustie M., Berthe L., De Resseguier T., Arrigoni M.: Laser Shock Waves: Fundamentals and Applications. Proceedings of the 1st International Symposium on Laser Ultrasonics: Science, Technology and Applications (2008), 1–6.
3. Peyre P.: Laser Shock Processing on Metal. Metals 7 *(*2017), 409.
4. John M., Kalvala P.R., Misra M., Menezes P.L.: Peening Techniques for Surface Modification: Processes, Properties, and Applications. Materials 14 (2021), 3841.
5. Cuenca E., Ducousso M., Rondepierre A., Videau L., Cuvillier N., Berthe L., Coulouvrat F. Propagation of laser-generated shock waves in metals: 3D axisymmetric simulations compared to experiments. Journal of Applied Physics. 128 (2020), 244903.
6. Sokol D.W., Clauer A.H., Dulaney J.L., Lahrman D.W.: Applications of laser peening to titanium alloys. Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science and Photonic Applications. Systems and Technologies, Technical Digest (CD) Optica Publishing Group (2005)
7. Zhang C., Dong Y., Ye C.: Recent Developments and Novel Applications of Laser Shock Peening: A Review. Advanced Engineering Materials 23 (2021), 2001216.

8. Ouyang P., Luo X., Dong Z., Zhang S.: Numerical Prediction of the Effect of Laser Shock Peening on Residual Stress and Fatigue Life of Ti-6Al-4V Titanium Alloy. Materials 15 (2022), 5503.
9. Ranjith Kumar G., Rajyalakshmi G., Swaroop S.: A critical appraisal of laser peening and its impact on hydrogen embrittlement of titanium alloys. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 223 (2019), 2371-2398.
10. Shen X., Shukla P., Yao F., Nath S., An Z., Lawrence J.: Laser Shock Peening of Orthopaedic Ti-6Al-7Nb: Evaluation of Topography, Wetting Characteristics, Microstructure and Residual Stress. International Journal of Peening Science & Technology 1 (2019), 137-154.
11. Jiao Y., He W., Shen X.: Enhanced high cycle fatigue resistance of Ti-17 titanium alloy after multiple laser peening without coating. International Journal of Advanced Manufacturing Technology 104 (2019), 1333–1343.
12. Huang S., Zhu Y., Guo W., Peng P., Diao X.: Effects of Laser Shock Processing on Impact Toughness of Ti-17 Titanium Alloy. High Temperature Materials and Processes 37 (2018), 325-332.
13. Wu J., Lin X., Qiao H., Zhao J., Ding W., Zhu R.: Microstructural Evolution and Surface Mechanical Properties of the Titanium Alloy Ti-13Nb-13Zr Subjected to Laser Shock Processing. Materials 16 (2023), 238.
14. Ocaña J., Porro A., Morales M., Iordachescu D., Díaz M., Ruiz de Lara L., Correa C., Gil-Santos A.: Laser Shock Processing: an emerging technique for the enhancement of surface properties and fatigue life of high-strength metal alloys J.L. International Journal of Microstructure and Materials Properties 8 (2013), 38-52.
15. Maawad E., Sano Y., Wagner L., Brokmeier H.-G., Genzel Ch.: Investigation of laser shock peening effects on residual stress state and fatigue performance of titanium alloys. Materials Science and Engineering: A 536 (2012) 82-91.
16. Shu S., Huang X., Cheng Z., Shen Y., He Z., Liu W.: Understanding the Relations between Surface Stress State and Microstructure Feature for Enhancing the Fatigue Performance of TC6 Titanium Alloy. Coatings 11 (2021), 1261.
17. Kanjer A., Lavisse L., Optasanu V., Berger P., Gorny C., Peyre P., Herbst F., Heintz O., Geoffroy N., Montesin T., Marco de Lucas M.C.: Effect of laser shock peening on the high temperature oxidation resistance of titanium. Surface and Coatings Technology 326 (2017), 146-155.
18. Fan Y., Wang Y., Vukelic S., Yao Y.L.: Wave-solid interactions processes in laser-shock-induced deformation. Journal of Applied Physics 98 (2005), 104904.
19. Kovalyuk B.P., Nikiforov Y.N., Nischenko M.M.: The phase conversion in stainless steel under LSW processing. Reviews on Advanced Materials Science 8 (2004), 34-40.
20. Majkowska-Marzec B., Sypniewska J.: Microstructure and mechanical properties of laser surface-treated ti13nb13zr alloy with MWCNTs coatings. Advances in Materials Science 21 (2021), 5-18.
21. Trzepieciński T., Szpunar M.: (2021). Multivariate modelling of effectiveness of lubrication of Ti-6Al-4V titanium alloy sheet using vegetable oil-based lubricants. Advances in Materials Science 21 (2021), 26-39.
22. Kosturek R., Grzelak K., Torzewski J., Wachowski M., Śnieżek L.: Microstructure and mechanical properties of Sc-modified AA2519-T62 laser beam welded butt joints. Advances in Materials Science 22 (2022), 57-69.
23. Kiani A., Radmanesh M. High-Energy Nanosecond Laser Pulses for Synthesis of Better Bone Implants. High Energy and Short Pulse Lasers. Ed. R. Viskup, Rijeka, Croatia, InTechOpen (2016).

24. Mizutani M., Honda R., Yuda A., Komotori J., Ohmori H.: Effects of Nanosecond Laser Fabrication on Bioactivity of Pure Titanium. Procedia CIRP 5 (2013), 242-246.
25. Seo B.Y., Son K., Son Y.-T., Dahal R.H., Kim S., Kim J., Hwang J., Kwon S.-M., Lee J.-M., Lee K.-B.: Influence of Dental Titanium Implants with Different Surface Treatments Using Femtosecond and Nanosecond Lasers on Biofilm Formation. Journal of Functional Biomaterials 14 (2023), 297.
26. Lont A., Górka J., Janicki D., Matus K.: The laser alloying process of ductile cast iron surface with titanium powder in nitrogen atmosphere. Coatings 12 (2022), 227.
27. Lisiecki A.: Study of optical properties of surface layers produced by laser surface melting and laser surface nitriding of titanium alloy. Materials 12 (2019), 3112.