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Interaction of Lasers of Various Types with Alloys Based on Ni and Ti

Commonly implemented nickel and titanium alloys are nowadays alloyed with many new elements. Obtained in this way, new Ti-alloys are of great practical significance in aircraft industry, while Ni-alloys are important in energetic and nuclear technique.

Selected alloys of titanium and nickel have been treated in vacuum by various thermo-mechanical regimes. Most of the samples have been exposed to laser beams in the air, at the atmospheric pressure, while some of the samples have been treated in vacuum conditions.Laser-induced modifications of the samples microstructures have been analyzed by various methods of investigation, which include optical- and electron-microscopy (SEM).

The heating up of the selected Ni- and Ti-alloys to the melting point, in selected regimes of laser operation, has been simulated by contemporary numerical methods.

Keywords: *laser, interaction, damage, alloys.*

1. INTRODUCTION

Nickel- and titanium-based materials could be classified for contemporary processing methods according to their magnetic properties, density, mechanical, thermal and other characteristics. Titanium is a material difficult to process, due to its high melting and boiling points. As for the nickel, a usual constraint in the processing of the nickel-based materials is to preserve the magnetic properties of the material, which assumes small HAZ (heat-affecting zone).

Chosen alloys did originate from the base material (Ti or Ni) by its alloying with specific inclusions thus changing its characteristics, which broadens the area of implementation. In that way, Ti-based alloys are of great interest to aircraft engineering and vehicle industry, while Ni-alloys are important for the electrical energy production, including all particular key construction parts in thermo- and hydro-power plants. Laser-based methods, contrary to the “classical”, recommend themselves for the processing of these – otherwise hard-to-process materials, because, according to their thermal properties they are more appropriate for the processing than aluminium or copper [1-9].

In this work, selected Ti-based alloys and Ni-based alloys have been experimentally treated with laser beams. For selected specific modes of laser operation, the interaction has been simulated for the temperature range between the room temperature and the melting point temperature. The analysis for other shapes of laser pulses could be performed by including the corresponding functions representing the pulse shape.

2. EXPERIMENT

2.1 Samples

Samples are Ni- and Ti-based alloys: Inconel 718 and IMI 318.6-4 [10-14]. Besides mentioned alloys, we treated elemental Ni and Ti samples. Some of the samples were of extreme purity and some of them are commercially available. Few of the specimens have “non laser” welded parts.

2.2 Exposition to laser beams

Nickel, titanium, and their alloys are exposed to various laser beams in the air and vacuum environments [3]. The lasers have been in the visible and infrared (IR) regimes, i.e. ruby, Nd^{3+}:YAG and CO_2 in free-generation and Q-switch regimes. The pulses lengths were from ns to ms, with different shapes. The pulse energies were from several mJ up to J. The lasers operated in both single- and multi-modes,

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and the samples have been exposed to single or multi-pulse beams. Most of the expositions have been performed under appropriate beam focusing and normal incidence. Most of the laser beams were polarized [15-20].

3. RESULTS

The samples are analyzed visually by optical and SEM microscopes. The results are presented in Figures 1, 2, 3, 4, 5 and 6.

The stripe-like samples No. 1 (with non-laser welded point) and No. 2 (without welding place) are analyzed. Two groups of damages are clearly expressed: three punctual damages in a row and two damages of larger sizes in the shape of irregular rectangle (square). It could be observed by naked eye as well as by stereoscopic microscope.

3.1 Sample 1

By analyzing on metallographic microscope with higher magnification (50X) on sample 1, it is shown that all damages are punctual of irregular circular shape of expressed topography. In the centre of the central part the shape of the material indicates melting and solidification in that zone. Colour change, at the edge of the damage area of the basic material, indicates a thermal front effect. In addition, in that area, zones of irregular shape can also be identified and they point out to oxidation processes near the damage. Damages in the form of irregular rectangles (squares) at these magnifications were shown to be an array of dark points in stripe configuration.

3.2 Sample 2

The analyses are the same as well as recording as for sample No. 1. The degree of oxidation of the damage is higher than for the sample No. 1. The formation and view are the same as for sample 1. The point-like damages are approximately of circular shape but the diameter can not be seen clearly. The melting of the material in the central part of the damage is induced, but the topography is of smaller expression than in the sample 1. In the case of square-like damage, the point-like damages in stripe configuration were not observed. The surface is like ionic etched. In the Figure 1 is presented sample with weld. Figures 2, 3 and 4 present samples without welds.

3.3 Ti samples

In the Figures 5 and 6 Ti samples exposed to ruby laser in vacuum and under atmospheric pressure are shown [3].

4. MATHEMATICAL MODEL OF INTERACTION

4.1 Theory

The case of the laser interaction with a thin plate specimen is considered. The assumption is that the

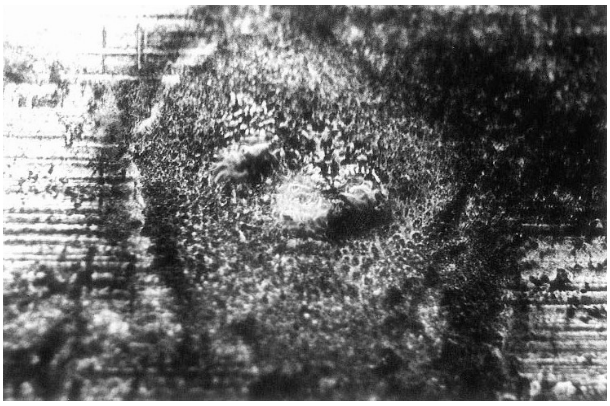

Figure 1. Micrograph of the Ti-alloy damage by TEA CO$_2$ laser, Spot 3; E$_{per\ pulse}$ = 85 mJ; 400X

Figure 2. Micrograph of the Ni-alloy damage by TEA CO$_2$ laser, Spot 2; 120 pulses; E$_{per\ pulse}$ = 85 mJ; 200X

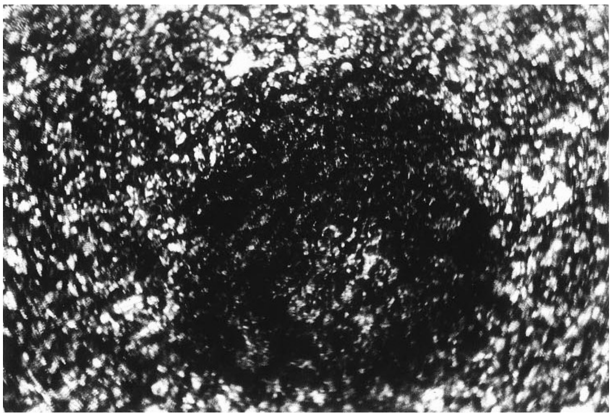

Figure 3. Micrograph of the Ni-alloy damage by TEA CO$_2$ laser, Spot 1; Pilot pulses; E$_{per\ pulse}$ = 85 mJ; 200X

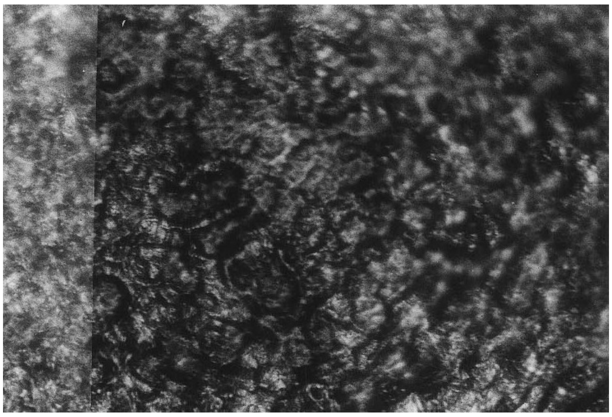

Figure 4. Micrograph of the Ni-alloy damage by TEA CO$_2$ laser, Spot 3; 300 pulses; E$_{per\ pulse}$ = 120 mJ; 400X

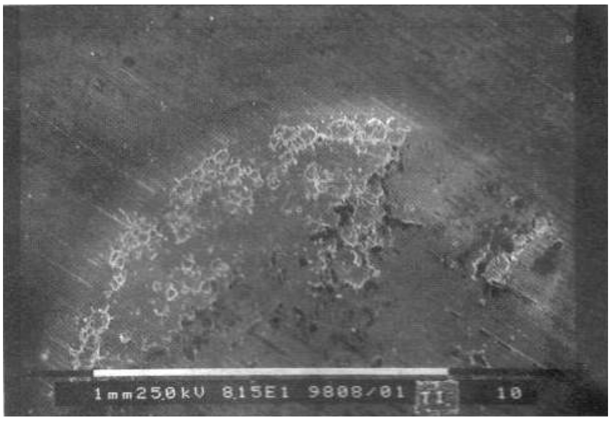

Figure 5. SEM micrograph of Ti-exposition in vacuum; E_{pulse} = 2.6 J; Ruby laser [3]

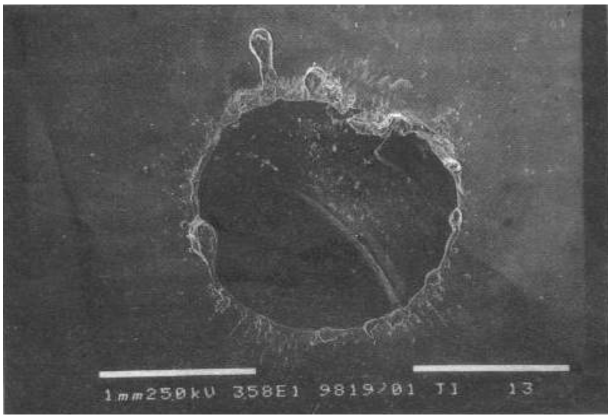

Figure 6. SEM micrograph of Ti-exposition in ambient atmosphere; E_{pulse} = 2.6 J; Ruby laser

thickness of plate specimens is smaller than other dimensions of the specimen and the diameter of laser beam. Under these circumstances edge thermal effects could be neglected. Due to axial symmetry of the considered problem the cylindrical coordinate system was chosen (Fig. 7). The second assumption is that laser-material interaction is modelled by thermal model, i.e. we consider only heating of the material up to the melting point. The absorption of laser radiation was assumed to occur in a thin surface layer on the upper side of the specimen. According to these approximations, the effects of the incident laser beam on the material were represented by a thermal flux on the upper side of the material.

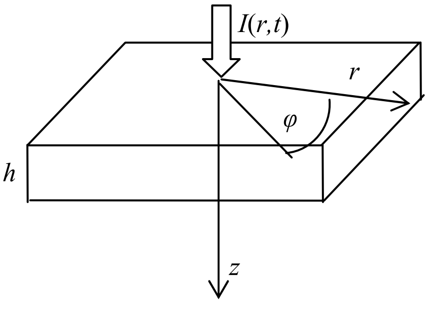

Figure 7. Geometry of the sample

The laser beam intensity was approximated by a product of two functions $q(r)$ and $\varphi(t)$, which gives spatial and temporal dependence of laser beam intensity, respectively. We assumed that thermal and optical parameters of the material do not depend on temperature in the temperature range of interest for this analysis, too. The thermal losses, corresponding to the heath transfer from rear surface of the material, were taken into account. According to these considerations, the heating of plate specimens could be described by the following partial differential equations (PDF) with corresponding boundary and initial conditions:

$$\begin{gathered}
\frac{1}{a}\frac{\partial T(z,r,t)}{\partial t} = \Delta T(z,r,t) \\
-\lambda\frac{\partial T}{\partial z} = A\varphi(t)\cdot q(r), \quad z=0 \\
-\lambda\frac{\partial T}{\partial z} = \alpha T, \quad z=h \\
T(z,r,0)=0 \\
T(z,\infty,t)=0 \\
t>0, \quad 0\le z\le h, \quad 0\le r
\end{gathered} \tag{1}$$

where: λ – coefficient of thermal conductivity, $a = \lambda/\rho c$, c – specific heat, ρ – material density, α – heat transfer coefficient which determines the rate of heat losses, h – plate thickness, A – absorption coefficient of the material and T is the difference between the interior domain and the ambient temperatures.

In case of Gaussian profile, the spatial distribution of the laser beam intensity can be expressed by the following relation:

$$q(r) = I_0\cdot\exp\left(\frac{r}{r_{ef}}\right)^2 \tag{2}$$

where $2{*}r_{ef}$ is effective diameter of the laser beam, I_0 is the laser radiation intensity in the beam centre.

Using **Laplace and Haenkel** transformations temperature distribution inside specimens, under above circumstances, for the case of Dirac's inductions i.e. for $\varphi(t) = \delta(t)$, where $\delta(t)$-Dirac function and Gaussian profile of laser beam can be expressed by the following relation [20]:

$$\begin{gathered}
T_\delta(z,r,t) = \frac{2AP_0a}{\pi\lambda h}\cdot\frac{e^{-\frac{r^2}{r_0^2+4at}}}{r_0^2+4at}\cdot \\
\cdot\sum_{n=1}^{\infty}\frac{\lambda\mu_n\cos\left(1-\frac{z}{h}\right)+\alpha h\sin\left(1-\frac{z}{h}\right)}{(\alpha h+\lambda)\sin(\mu_n)+\lambda\mu_n\cos\mu_n}e^{-a\left(\frac{\mu_n}{h}\right)^2t} \\
r\ge 0, \quad 0\le z\le h, \quad t>0
\end{gathered} \tag{3}$$

where all symbols have the same meaning like ones in (1). The constants μ_n are given as solution of transcendental equation by the following relation:

$$\mu_n\,\mathrm{tg}\,\mu_n = \frac{h\alpha}{\lambda} \tag{4}$$

For top head profile of laser beam temperature distributions T_δ (z,r,t) can be expressed in a similar way by the next relations:

$$T_\delta(z,r,t)=\frac{2AP_0a}{r_0\pi\lambda h}\cdot$$

$$\cdot\sum_{n=1}^{\infty}\frac{\lambda\mu_n\cos\left(1-\frac{z}{h}\right)+\alpha h\sin\left(1-\frac{z}{h}\right)}{(\alpha h+\lambda)\sin(\mu_n)+\lambda\mu_n\cos\mu_n}e^{-a\left(\frac{\mu_n}{h}\right)^2t}\cdot$$

$$\cdot\int_0^\infty J_1(r_0p)J_0(rp)\,\mathrm{d}p$$

$$r\geq 0,\quad 0\leq z\leq h,\quad t>0 \qquad (5)$$

where J_1 and J_0 are **Bessel's** functions of first kind, respectively, $2*r_0$ – diameter of beam and P_0 – effective power of beam i.e. $P_0 = I_0*S_{\text{eff}}$, S_{eff} – effective area of laser beam and $S_{\text{eff}} = r_0^2\pi$.

Specially, the temperature distributions T_δ along z axis versus time for $r = 0$ (centre of beam) and $r = r_0$ can be expressed by the following relations:

$$T_\delta(z,0,t)=\frac{2AP_0a}{r_0\pi\lambda h}\cdot$$

$$\cdot\sum_{n=1}^{\infty}\frac{\lambda\mu_n\cos\left(1-\frac{z}{h}\right)+\alpha h\sin\left(1-\frac{z}{h}\right)}{(\alpha h+\lambda)\sin(\mu_n)+\lambda\mu_n\cos\mu_n}e^{-a\left(\frac{\mu_n}{h}\right)^2t}\cdot\frac{1-e^{-\frac{r_0^2}{4at}}}{r_0}$$

$$T_\delta(z,r_0,t)=\frac{AP_0a}{r_0\pi\lambda h}\cdot$$

$$\cdot\sum_{n=1}^{\infty}\frac{\lambda\mu_n\cos\left(1-\frac{z}{h}\right)+\alpha h\sin\left(1-\frac{z}{h}\right)}{(\alpha h+\lambda)\sin(\mu_n)+\lambda\mu_n\cos\mu_n}e^{-a\left(\frac{\mu_n}{h}\right)^2t}\cdot$$

$$\cdot\frac{1-e^{-\frac{r_0^2}{4at}}}{r_0}I_0\left(\frac{r_0^2}{2at}\right)$$

$$r\geq 0,\quad 0\leq z\leq h,\quad t>0 \qquad (6)$$

where I_0 is modified Bessel's functions of first kind. The temperature difference distribution inside the material for arbitrary temporal distribution of the laser beam intensity is obtained using the convolution integral given by the relation:

$$T(z,r,t)=\int_0^t\varphi(t-\tau)T_\delta(z,r,\tau)\,\mathrm{d}\tau\,. \qquad (7)$$

4.2 Numerical results

The distribution of temperature difference inside Ti- and Ni-alloys specimen obtained according to the (3) and (7) for TEM$_{00}$ mode of laser beam during one laser pulse only, is given in Figures 8, 9, 10 and 11. The Gaussian profile of beam is taken into account.

Some data about power distribution of TEM$_{00}$ mode are: wavelength 10.6 μm, total pulse length 1.88 μs, pulse width FWHM′121 ns, pulse energy 85 mJ, average pulse power P_m = 45.213 kW, repetition rate n = 2.2 Hz, T = 454.5 ms, etc.

The numerical is performed for the constants, some of which are presented in Table 1.

Table 1. Thermodynamical constants

Alloy	c [J/kgK]	T_m [°C]	ρ [kg/m^3]	coef. abs.
Ni-alloy	435	1260 – 1336	8190	0.059
Ti-alloy	550	1680	4460	0.06

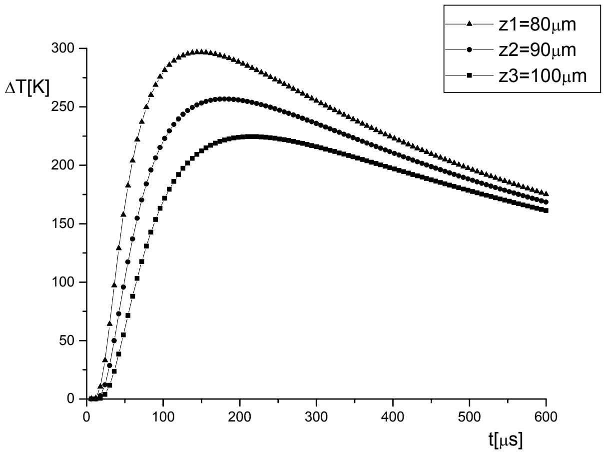

Figure 8. Temperature distribution for TEM$_{00}$ mode in centre of beam for Ni-alloy

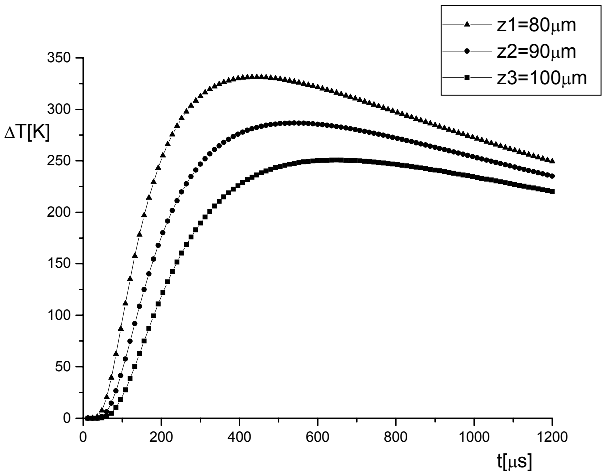

Figure 9. Temperature distribution for TEM$_{00}$ mode in centre of beam for Ti-alloy

The temperature distribution is obtained by convolution of the pulse response and temporal distribution of incident intensity according to (7).

In Figures 8 and 9 the distribution of temperature difference inside Ti- and Ni-alloy specimens obtained according to (6) and (7) for multimode laser working regime, and the top-head profile of beam was supposed. The calculations can be performed in a similar way for specific laser pulse: here is the simulation for pulse shape of CO$_2$ laser [16-18]. The respective power distribution for multimode working regime is shown.

5. DISCUSSION AND CONCLUSION

The theoretical relationship between crater and diameter of laser damage in various dynamical regimes are sometimes very distant from experimental results, so improvement of existing models is always needed. Ni- and Ti-alloys have very different physical properties and it seems to be very obvious that the respective

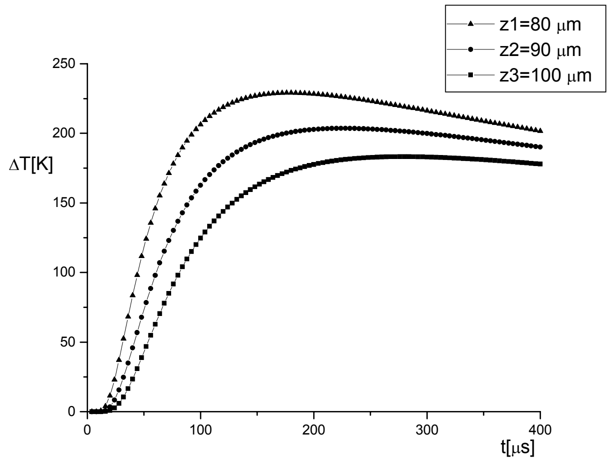

Figure 10. Temperature distribution for multimode regime in centre of beam for Ni-alloy

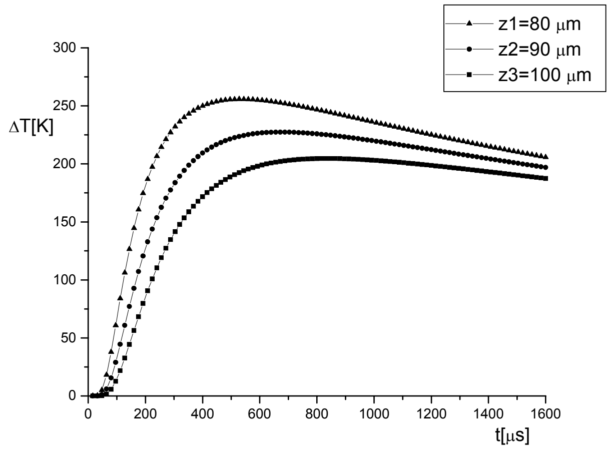

Figure 11. Temperature distribution for multimode regime in centre of beam for Ti-alloy

temperature distributions claim these variations. It seems that as materials with higher thermal conductivity have some kind of higher thermal “inertion” i.e. the cooling and heating is slower than for material of lower thermal conductivity.

Among other applications the laser was successfully applied for the radioactive decontamination process of metal surface.

Damages provoked on Ni- and Ti-based alloys show complex structures, having in mind that for multimode or single mode regimes there are various shapes and surfaces according to lasing regimes. It seems that multimode structure and laser intensity could be analyzed by investigating damage processes (depth profiling and material ejections). The shape of damages is complex in multimode and almost circular in monomode lasing regime.

Simulation of laser material interaction for Ni- and Ti-based alloys is performed by contemporary numerical methods and by thermal modelling [19-22]. The calculations are done with the assumptions that total energy is absorbed by materials and transported according to their thermal properties. In spite of sophisticated possibility of numerical calculations the real material behaviour versus definite laser beam is more complicated. First of all, the online measurement of the coefficient of reflection in temporal resolution could be performed only by sophisticated measuring system consisting of two lasers. One of the lasers serves for evaluating the coefficients of reflections with low intensity and the second is an interacting one. The interesting facts could be the number of pulses which lead to material melting, or boiling point or other critical points.

The investigation of component in the interaction zone will be of further interest, depending on the quality of the alloys (EDX measurements, SIMS). The high Nickel content is of importance. Depletion of some component could be closely linked to the thermal characteristic (melting, boiling points) and respective heat of transition.

For the alloys the most interesting temperatures are phase transition temperatures. In our experiments almost all interesting temperatures are included, 540 ºC and 1200 ºC, judging by damage view and numerical calculations.

The most important fact is that two pictures which can be obtained after study of materials after laser beam expositions, and after study of the ejected material from the sample (droplet, ions, clusters total ejected) in references are inconsistent. This fact is a good starting point for future studies.

The holography, Raman Brillouin spectra as well as IR spectra, mass spectra (SIMS, MRSI) and laser tomography could give a lot of new performances, which have to be compared with more classical measurements describing materials [23-32]. The effects of nonlinear optics are present during the interactions. These provoked effects, we can not take into account before knowing the total interactions. This is of great importance when dealing with fempto and atto pulses (change of interaction models is required). Considering laser processing, Ni and Ti are in two groups of materials, with enough laser beam absorption performances, but, Ti is with higher melting and boiling points.

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ИНТЕРАКЦИЈА РАЗЛИЧИТИХ ТИПОВА ЛАСЕРА СА ЛЕГУРАМА БАЗИРАНИМ НА НИКЛУ И ТИТАНИЈУМУ

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Савремене легуре на бази никла и титанијума, са већим бројем нових елемената, имају широку примену. Тако добијене нове легуре титанијума су од великог практичног значаја у ваздухопловству, а новодобијене легуре никла у енергетици и нуклеарној техници.

У оквиру овог рада су приказани резултати третирања легура титанијума и никла сноповима ласера у ваздуху, на атмосферском притиску, као и појединих узорака у вакуумским условима.

Добијене ласерске модификације микроструктура узорака су анализиране различитим методама испитивања, које укључују оптичку и електронску микроскопију (SEM). Савременим нумеричким методама је, за изабране режиме рада ласера, симулирано грејање до тачке топљења одговарајућег материјала.