JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 12, No. 4, April 2010, p. 933 - 936

The theoretical and experimental study of some metals heating and melting under the action of laser radiation

S. DINU, C. OROS, M. VOICU*, G. DIMA, C. STIHI
"Valahia" University of Targoviste, Faculty of Sciences and Arts,
28 Unirii street, Targoviste, Romania

This study presents theoretical and experimental results on the laser irradiation of some metals (titanium, nickel, aluminium, copper, steel), using an Nd:YAG laser. The theoretical study involves the solving of heat equation for half-infinite targets. The determination of the temperature at the surface of the irradiated material allows quantitative estimations regarding the induced thermo deformation and the involved phase transition, in our case, the melting. The confrontation with experience is achieved through the comparison of the thermo deformation sizes and obtained craters and of the others related parameters with the direct microscopically measurements. The calculated values are in proper correlation with the experimental ones, the observed differences having as major cause the insufficiently precise knowledge of the involved physical values of observables, at high reached temperatures on the irradiated surfaces.

(Received April 7, 2010; accepted April 26, 2010)

Keywords: Metal, Steel, Nd:YAG laser, Thermo deformation, Laser melting, Laser radiation

1. Introduction

Exist, in present, a large variety of papers linked by the physic-chemical and technical properties of the metals which will be study. The special qualities of these materials recommend them to be used in various domains. More then that, one can say that these metals are indispensable elements in our times activities.

As by laser irradiation the superficial properties of metals can be modified, it is important to study which are the mechanical, thermic, electrical or optical effects of this irradiation and how can be improved some characteristics for a better response of material to requests.

2. Experimental

The experimental assembly used in the irradiation experiences is composed from an Nd:YAG laser, an optical microscope, a light source and metallic samples. The samples have cylindrical shape, with height $h \approx 5mm$ and base diameter $d \approx 20mm$.

The characteristics of the emitted radiation by Nd:YAG laser are: the wavelength $\lambda = 1{,}06 \mu m$ (IR); the diameter of laser spot $D_s = 0{,}4\ mm$, the length of laser pulse $\tau_p = 3ms$ (irradiation regime is monopulse).

After irradiation, the analysis of irradiated surfaces has been done with an optical microscope whose accuracy in the estimate of the created drops (dilatations and craters) is $2 \mu m$.

3. Results and discussion

The samples have been irradiated differently through the modification of pulse energy. The adequate intensities have been established with the following relation:

$$I_i = \frac{E_i}{S \cdot \tau_p} \quad , \; i = \overline{1,10}, \tag{1}$$

where $S = \pi \frac{D_s^2}{4}$ representing the area of irradiated surface and τ_p representing the laser pulse length.

The measured dimensions of formed thermo dilatations (+) or craters (-), matched to the intensities given by the relation (1), are presented in table 1 ($1div = 2\mu m$).

Table 1. The measured dimensions of formed thermo dilatations (+) or craters (-)

Sample	1	2	3	4	5	6	7	8	9	10
E_i (J)	$\leq 0{,}1$	0,1	0,3	0,5	0,7	0,9	1,1	1,3	1,5	1,7
$I_i(10^9 W/m^2)$	-	0,3	0,8	1,3	1,9	2,4	3	3,4	4	4,5
$\Delta z_i(Ti)\ (\mu m)$	0	0	+2	+2	+4	+5	-40	-52	-70	-110

Sample	1	2	3	4	5	6	7	8	9	10
$\Delta z_i(Al)$ (μm)	0	0	0	0	+6	+8	-70	125	180	215
$\Delta z_i(Cu)$ (μm)	0	0	0	0	-10	-15	-25	-35	-75	-120
$\Delta z_i(Ni)$ (μm)	0	+2	+3	-8	-22	-40	-75	-60	-95	-105
$\Delta z_i(steel)$ (μm)	0	0	-6	-18	-38	-55	-68	-80	-80	-96

These results will be interpreted on the bases of a thermic model of interaction between the laser radiation and metallic samples.

Thus, the spatial – temporal dependence of the reached temperature in the target, *T(z,t),* can be established using the one-dimensional equation of heat propagation in a solid medium, whose form is:

$$\rho c \frac{\partial T}{\partial t} = K_T \frac{\partial^2 T}{\partial z^2} + \alpha A I_0 e^{-\alpha z}, \tag{2}$$

where *z* is the depth in the target and *t* is the irradiated time. The measurements *ρ, c, A, α* and I_0, depending all of temperature, represent the density, specific heat, the absorptivity, the absorption coefficient of sample and the intensity of laser radiation on target surface. For simplicity, in the next calculations, the Gaussian distributions of intensity in laser beam have been approximated with uniform distributions based on the equation $I_{0i} = 0{,}7 I_i$, $i = \overline{1{,}10}$. The values of measurements mentioned above correspond to temperature *T = 300K* and for the absorptivity was used the Fresnel equation:

$$R = \frac{(n-1)^2 - k^2}{(n-1)^2 + k^2}, \tag{3}$$

where *n* and *k* correspond the wavelengh $\lambda = 1{,}06 \mu m$ [14].

Because the laser radiation is, for the metallic sample, a superficial heat source, meaning between the thickness of target (*h*), the diameter of laser spot (D_s) and the thermic diffusion length ($l_{th} = \sqrt{\pi \chi_T \tau_p / 2}$) exists the relation $h >> D_s > l_{th}$ (half-infinite targets), the solution of equation (2) has the form [6]:

$$T(z,t) = \frac{2AI_0}{K_T}\sqrt{\chi_T \cdot t} \cdot ierfc \frac{z}{2\sqrt{\chi_T \cdot t}} \tag{4}$$

For *z=0* (at the sample surface) and $t = \tau_p$, the relation (4) becomes:

$$T(0,\tau_p) = \frac{2AI_0}{K_T}\sqrt{\chi_T \cdot \tau_p}. \tag{5}$$

The experiments made respect the condition mentioned above, which can be observed comparing the next values: *h=5mm*; D_s*=0,4mm*; l_{th}*= 0,14mm* for titanium, l_{th}*= 0,47mm* for aluminium, $l_{th} = 0{,}98\ mm$ for copper, l_{th}= 0,21*mm* for nickel and $l_{th} = 0{,}12 mm$ for steel.

The values of physic parameters from relation (5), for metals which we used, are presented [7], [13], [14] in Table 2.

Table 2: The values of physic parameters for some materials

	Titanium	*Aluminium*	*Copper*	*Nickel*	*Steel*
Absorptivity, A (%)	7	6	3	28	27
Thermic conductivity, K_T (J/msK)	22	236	1401	83	26
Density, ρ (Kg/m^3)	4500	2700	8900	8800	8000
Specific heat, c (J/kgK)	520	902	380	460	470
Thermic diffusivity, χ_T (10^{-4} m^2/s)	0,09	0,96	4,14	2,3	0,07
Melting temperature, $T_{melting}$ (K)	2073	930	1357	1728	1808
Vaporization temperature, T_{vap} (K)	3523	2543	2310	2913	2573

A first verification of the used model is achieved comparing the superficial density of electromagnetic energy needed for the beginning of metallic samples melting, calculated with the formula [6]:

$$w_{em\ theor} = \sqrt{\pi \rho c K_T \tau_p}\left(T_{melting} - T_0\right)/2A, \tag{6}$$

with the experimental value:

$$w_{em\,\exp} = \frac{E_{melting}}{S}, \tag{7}$$

where $E_{melting}$ represent the value of laser pulse energy which for craters start to appear (the first values with "+" from table 1). The calculated and experimental values for each metal are mentioned in the table 3.

Table 3. The calculated and experimental values of the superficial density of electromagnetic energy

	Ti	*Al*	*Cu*	*Ni*	*Steel*
$w_{em\ teor}$ $(10^6\ J/m^2)$	8,9	12,7	12	4,6	2,7
$w_{em\,\exp}$ $(10^6\ J/m^2)$	8,7	3,6	10,4	4	2,4

Interesting dates are given by the estimation of the time needed to the laser radiation to initiate the melting process for the used metals (table 4). It is used the relation (8), obtained from the application of thermic model of interaction [6]:

$$t_{top} = \frac{K_T^2 \cdot T_{top}^2}{4A^2 I_{top}^2}, \tag{8}$$

where $I_{top} = \frac{E_{top}}{S\tau_p}$.

Table 4. The time needed to the laser radiation to initiate the melting process

Metal / Time	*Ti*	*Al*	*Cu*	*Ni*	*Steel*
$t_{melting}\ (ns)$	12	370	270000	39	12

It may be done as well a theoretical estimation of length of the craters formed in the metallic sample based on an approximated formula which was obtained with the same thermic model [6]:

$$\Delta z_{crater} \cong \frac{D_s}{4}\left(\frac{T_{vap}}{T_{melting}} - \frac{T_{melting}}{T_{vap}}\right). \tag{9}$$

The results are mentioned in the table 5 and can be compared to the values with "-" from table 1.

Table 5. The length of the craters formed in the metallic sample.

	Ti	*Al*	*Cu*	*Ni*	*Steel*
$\Delta z_{crater}\ (\mu m)$	73	350	112	110	72

Another confrontation with the experience is possible, in the case of Ti, Al and Ni from the estimation of the linear dimensions of the thermo dilatation, based on the linear dilatation and the comparison of these with the measurements realised using optical microscope (table 1, values with "+"). Thus, considering the length dilatation of the cylinder with z_0 high and $S = \pi\frac{D_s^2}{4}$ base area, it can be written:

$$\Delta z_{i\,theor} = \alpha z_0 \Delta T, \tag{10}$$

where: z_0 is considered approximately equal with the length of thermic diffusion in the metal, $z_0 \approx l_{th}$; $\alpha(Ti) = 1{,}08\cdot10^{-5}\ K^{-1}$, $\alpha(Al) = 2{,}3\cdot10^{-5}\ K^{-1}$, $\alpha(Cu) = 1{,}7\cdot10^{-5}\ K^{-1}$, $\alpha(Ni) = 1{,}3\cdot10^{-5}\ K^{-1}$, $\alpha(steel) = 1{,}2\cdot10^{-5}\ K^{-1}$; $\Delta T_i \cong T_i - T_0$ with $T_0=273\ K$; T_i is calculated with the equation (5).

The experimental values of thermo dilatations are those with "+" from table 1 and the comparison is presented in the tables 6, 7 and 8. Were not been observed thermo dilatations on copper and steel.

Table 6. Comparison between experimental and theoretical values for Ti

Sample (Ti)	*1*	*2*	*3*	*4*
$T_i\ (K)$	800	1300	1900	2400
$\Delta z_{itheor}\ (\mu m)$	0,79	1,54	2,44	3,19
$\Delta z_{iexp}\ (\mu m)$	2	2	4	5

Table 7. Comparison between experimental and theoretical values for Ni.

Sample (Ni)	*1*	*2*
$T_i\ (K)$	510	1300
$\Delta z_{iteor}\ (\mu m)$	0,65	2,8
$\Delta z_{iexp}\ (\mu m)$	2	3

Table 8. Comparison between experimental and theoretical values for Al.

Sample (Al)	*1*	*2*
$T_i\ (K)$	510	640

Δz_{itheor} (μm)	2,6	4
Δz_{iexp} (μm)	6	8

An interesting element is related to the comparison, using the optical microscope, of the thermo dilatation form with that of the intensity distribution in the laser beam (figure 1). This suggests the fact that in the central zone of the beam, because of the higher values (Gaussian distribution), the reached temperature in the spot centre is higher, therefore the dilatation extent will be higher too.

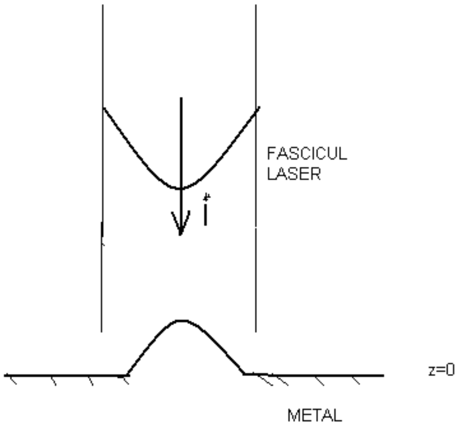

Fig. 1. Comparison of the thermodilatation form with the intensity distribution form in the laser beam.

4. Conclusions

1. It has been possible to observe an approach close enough to the theoretical results with the experimental ones in the determination of the superficial density of the needed energy for induction of analysed metals melting. For aluminium, the concordance is not very good, a possible reason being that the Al surface transforms in Al_2O_3 in contact with the air, so the specific physical parameters used in caculation were different.

2. Another important conclusion is based on the relation between the time needed to initiate the melting process and the thermic conductivity, respectively the metal absorptivity, meaning that this time is as higher as the thermic conductivity is higher (the heat spread faster in the material) and the absorptivity is lower, fact well showed in calculations at least for the explanation of maximum time at copper and minimum time at steel.

3. Good concordances have been observed to four from those five metals for melting depth. The theoretical values are included in experimental ones, excepting aluminium, probably for the reason meantioned at point 1.

4. The mechano-thermic model for estimating the shown up thermodilatation after the irradiation was less suitable, excepting nickel thereupon the theoretical value is close to the experimental one. The explanation is simple: the dilated and warmed volume is much more higher then the considerate one in the application of the thermic dilatation law, fact that appreciably minimizes the theoretical values of the dilatation at the samples surfaces.

This suggests that, although the values of the involved physical parameters, in calculations, are insufficiently known, specially at high temperature reached at the samples surfaces, the used thermic model was good enough offering correct informations linked with mealting process and estimations according the experimental notes. *This means that the model can be used with higher trust in other experiences of laser irradiation of solid materials.*

Finally, it is obvious the necessity to continue this type of experiences for other materials for more precise estimations on the validity of the thermic model of interaction.

References

[1] U. Diebold, Surf. Sci. Rep.**48,** 53 (2003).
[2] T. Le Mercier, J-M. Mariot, P. Parent, M-F. Fontaine, C. F. Hague, M. Quarton, Appl. Surf. Sci. **86**, 382 (1995).
[3] T. D. Robert, L. D. Laude, V. M. Geskin, R. Lazzaroni, R. Gouttebaron, Thin Solid Films **440,** 268 (2003).
[4] Y-J. Li, T. Matsumoto, N. Gu, M. Komiyama, Appl. Surf. Sci. **237,** 374 (2004).
[5] Dieter Bauerle, Laser processing and chemistry, Springer, Berlin (2000).
[6] I. Ursu, A. Prokhorov, Interacţia radiaţiei laser cu substanţa, Ed.Academiei RSR, Bucureşti (1986).
[7] E. D. Palik, Handbook of Optical Constants of Solids (Academic Press, Orlando,1985)
[8] R.C.Weast, CRC Handbook of Chemistry and Physics, 67th edition (CRC Press, Boca Raton, 1986).
[9] M. Wautelet, E.D.Gehain, Semicond. Sci. Technol. **5** 246 (1990).
[10] M. Wautelet, A. Jardin, L. Laude, Plasma formation during excimer laser irradiation of thin selenium films in air, Laser-Assisted Processing II, The Hague, SPIE-vol. 1279, 115, (1990).
[11] O. Van Overschelde, S. Dinu , G. Guisbiers, F. Monteverde, C. Nouvellon, M. Wautelet – Excimer laser ablation of thin titanium oxide films on glass, Applied Surface Science **252**, 4722 (2006).
[12] M. Wautelet, P. Quenon, A. Jardin, Origin of laser-assisted and doping-assisted phenomena in semiconductors, Semic. Sci. Technol. **3**, 54 (1988).
[13] David R. Lide, Handbook of Chemistry and Physics, 8th Edition (2006-2007).
[14] W. Martienssen and H. Warlineant, Springer Handbook of Condensed Mater and Materials Data (2004).

---

[*] Corresponding author: mary_voicu@yahoo.co.uk