

# Modeling of pulsed laser ablation of aluminum under the action of infrared nanosecond laser pulses

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**Abstract.** The paper presents the results of numerical simulation of aluminum ablation process that is caused by a series of incident nanosecond pulses on a wavelength  $\lambda=1064$  nm. The mechanism of normal evaporation and the effect of plasma shielding were taken into account. As a result of mathematical modeling the ablation depth was obtained. It is shown that plasma shielding reduces the effectiveness of ablation process much more than cooling of the aluminum surface between pulses.

## 1 Introduction

Numerous studies were devoted to the application of pulsed laser ablation in production of nanomaterials and clusters, pulsed laser deposition, spectroscopy, laser micromachining, chemical analysis [1]–[3]. Laser micromachining of metals has found the most widespread industrial application that contributed to massive experimental and theoretical studies. The objective of those investigations was obtaining the dependence of ablation depth from the laser parameters (pulse duration and frequency, laser intensity, wavelength, etc.). Some of them [4], [5] indicated the possibility of achieving a qualitative agreement of the calculations and experimental data. Since most of nanosecond pulsed industrial laser micromachining systems operate in the following parameters range:  $4.5 \text{ ns} \leq \tau \leq 50 \text{ ns}$ ,  $10^7 \text{ W}/(\text{cm}^2) \leq I \leq 10^{11} \text{ W}/(\text{cm}^2)$ ,  $10 \text{ Hz} \leq f \leq 10^5 \text{ Hz}$ , the necessity for a detailed study of laser-material interaction processes at these regimes seems apparent [6], [7].

In the above range of parameters the basic mechanisms of ablation are thermal (normal) evaporation and phase explosion [8]. A significant material removal occurs by thermal evaporation mechanism when a surface temperature is greater or equal to the boiling point of substance at atmospheric pressure. Heating of metal surface is carried out by absorption of the incident radiation by free-electron gas, that further transmits laser energy to the lattice in about  $10^{-13}$  s [4]. Because of heating and subsequent melting (happening in few picoseconds) molten layer is formed. Onwards atoms with energy higher than the binding

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energy of metal are ejected from it in process of thermal evaporation. At high values of laser intensity the temperature of molten layer exceeds the boiling point. The ablation process simulation of various materials such as dielectrics and alloys is rather complicated due to lack of information on these material properties at high temperature. On the other hand, ablation of pure metals such as aluminum, silver, copper and gold is investigated more thoroughly.

In the process of pulsed laser ablation plasma cloud is formed above the metal surface, which shields the incident radiation [8]. Screening effect is mainly influenced by the temperature of plasma and the laser wavelength. Plasma temperature increases during laser pulse impact due to the absorption of the incident flux. Thus, the temperature of plasma is associated with a characteristic evaporation temperature  $T_{\text{vap}}$  above which the metal ablation proceeds.  $T_{\text{vap}}$  is considered to be in a range of  $0.85T_c \leq T_{\text{vap}} \leq 0.9T_c$  [8].

## 2 Theoretical model

The heat-flow equation is used to describe the evolution of the metal temperature during laser energy absorption [5]:

$$\frac{\partial T}{\partial t} - v(T_s) \frac{\partial T}{\partial x} = \frac{\lambda}{\rho c_p} \frac{\partial^2 T}{\partial x^2} + \frac{1}{\rho c_p} \alpha I(t)(1-R) \exp(-\alpha x) \exp(-A), \quad (1)$$

where  $v(T_s)$  - velocity of surface recession,  $T_s$  - surface temperature,  $\lambda$ ,  $\rho$ ,  $c_p$  - correspondingly thermal conductivity, mass density and specific heat respectively,  $R$  - metal surface reflectivity,  $A$  - optical thickness of the plasma,  $\alpha$  - absorption coefficient, which depends on the laser wavelength,  $I(t)$  - intensity of laser radiation [4] calculated by equation:

$$I(t) = \frac{F}{\tau} \exp \left[ -4 \ln(2) \left( \frac{t - 1.5\tau}{\tau} \right)^2 \right], \quad (2)$$

where  $F$  is fluence,  $\tau$  - pulse duration (FWHM),  $t$  is the current time. The initial and boundary conditions are:

$$T(x, 0) = T_0, \lambda(T) \frac{\partial T}{\partial x} \Big|_{x=0} = Lv(t), T(x_0, t) = T_0, \quad (3)$$

where  $L$  - latent heat of vaporization,  $T_0=300$  K - initial temperature of the metal,  $x_0$  - initial metal thickness.

The velocity of the evaporation front  $v(T_s)$  is evaluated by Hertz-Knudsen equation combined with Clausius-Clapeyron equation:

$$v(T_s) = 0.82 \frac{p_b}{\rho} \sqrt{\frac{m}{2\pi k_b T_s(t)}} \exp \left[ \frac{L}{k_b} \left( \frac{1}{T_b} - \frac{1}{T_s(t)} \right) \right], \quad (4)$$

where  $p_b$  - atmospheric pressure,  $m$  - mass of the aluminum atom,  $k_b$  - the Boltzmann constant,  $T_b$  is the boiling temperature under reference pressure.

To account the plasma shielding effect we used model developed in [8]. Optical thickness of plasma cloud is calculated by:

$$A = aDx + bE_a(t), \tag{5}$$

where  $a = \alpha_{plas}(T_{vap})$ ,  $b = ((\gamma - 1)/k_b) [(\partial \alpha_{plas}) / \partial T]$  – coefficients of plasma screening (constant at a temperature of vaporization  $T_{vap}$ ),  $\gamma$  - the effective adiabatic exponent,  $E_a$  - density of the absorbed radiation energy:

$$E_a(t) = \int_0^t I_0(t') [1 - \exp(-A(t'))] dt'. \tag{6}$$

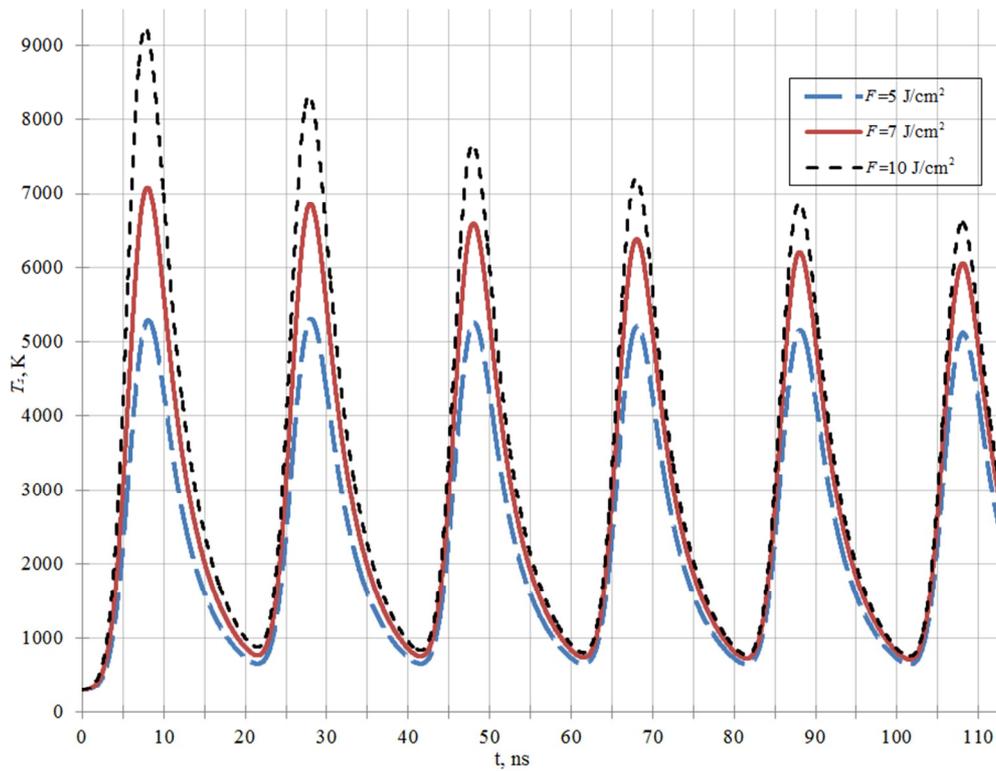
### 3 Results of modelling and discussion

The boundary value problem (1-6) was solved by the finite difference method using implicit stable Crank-Nicholson scheme. The time step was 0.5 ps; the space step – 1 nm. Table 1 shows the values parameters used in calculations.

**Table 1.** Parameters of modelling [4].

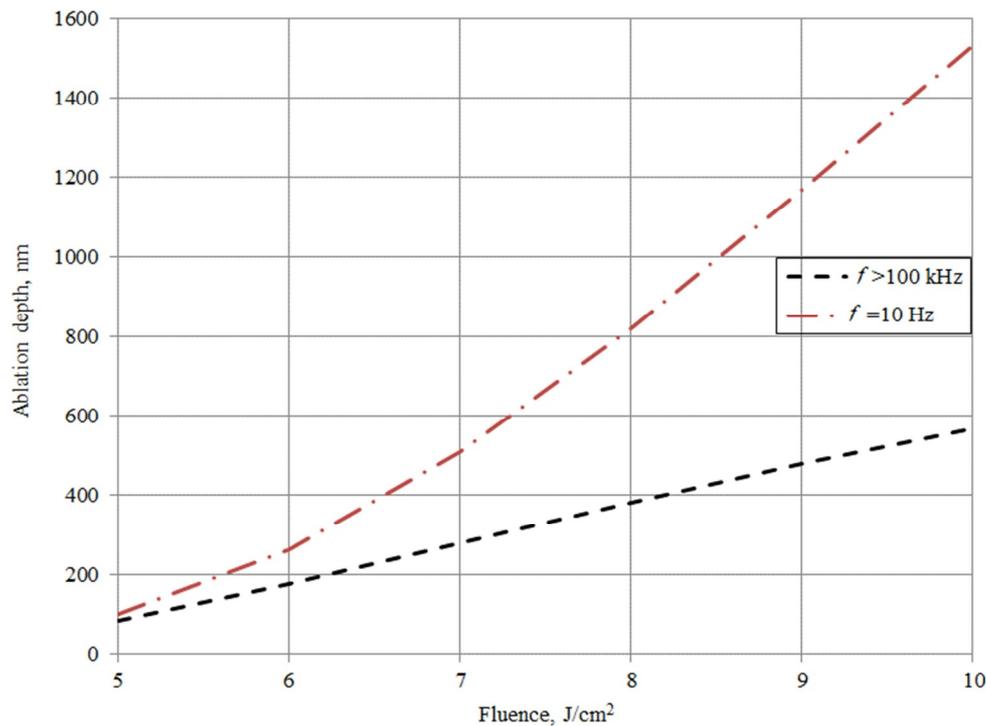
Mass density ( $\rho$ )	2700 kg/m <sup>3</sup> [9]
Heat capacity ( $C_p$ )	940 J/(kgK) [5]
Thermal conductivity ( $\lambda$ )	2.37 W/(cmK) [9]
Latent heat of evaporation ( $L$ )	1.05 MJ/kg [5]
Boiling temperature ( $T_b$ )	2730 K [9]
Absorption coefficient ( $\alpha$ )	$1.5 \times 10^{-6} \text{ m}^{-1}$ [9]
Reflectivity ( $R$ )	0.8
Plasmas optical thickness ( $A$ )	Equations (5-6)

A series of 10 pulses were produced with different repetition rates. In the first case, the frequency  $f > 100$  kHz, in the second:  $f = 10$  Hz. Below is a plot of the surface temperature versus time for the first six pulses at a high repetition rate ( $f > 100$  kHz).



**Fig. 1.** Dependence of surface temperature on time at  $f > 100$  kHz.

As you can see in figure 1, each subsequent pulse at  $F=10 \text{ J/cm}^2$  heats the surface less than previous pulse. Since we supposed that under condition at  $f > 100$  kHz the plasma does not have sufficient time to expand, we can conclude this is due to the presence of a plasma optical thickness that grows in the process of absorbing energy of incident laser and because of ablation with the aluminum surface. At  $F=5 \text{ J/cm}^2$  there is no significant difference between surface temperatures. Apparently this is due to the very small volume of the removed material at the end of the first pulse.



**Fig. 2.** Impact of fluence on the ablation depth for different repetition rates.

In order to reveal the role of plasma shielding on the ablation process, we turn to figure 2. In figure 2 the impact of fluence on the ablation depth is presented. It is seen that for independent pulses ( $f=10$  Hz) the ablation depth is the greater, the larger the incident fluence. This means that the energy spent on heating the plasma is greater than on the metal heating from room temperature to a temperature  $T\sim 850$  K.

## 4 Conclusion

Using the methods of mathematical modeling, the process of nanosecond pulsed laser ablation of aluminum was studied. The main emphasis was to compare two fundamentally different regimes of multi-pulse ablation process: regime of independent pulses and of consistent pulses. The mode of independent pulses is more energy-efficient from the point of view of the mass being ablated. It is shown that plasma shielding reduces the effectiveness of ablation process much more than cooling of the aluminum surface between pulses.

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