On Different Regimes of Condensed Matter Ablation Depending on Intensity and Duration of Absorbed Electromagnetic Pulses

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Abstract— It is shown that one should take into account rather small radiation penetration length in metal (Al) to describe properly nanosecond laser induced explosive (volume) boiling process. The result is obtained in the framework of molecular dynamic simulations combined with continual description of metal electron subsystem.

Absorption of intense electromagnetic pulses gives rise to various nonequilibrium processes in condensed matter which result in ablation of irradiated materials. These processes are investigated theoretically and experimentally for many decades (see, e.g., [1–9] and references therein). However, some of the problems in laser ablation are not yet completely resolved.

Laser-matter interaction depends on laser pulse intensity and duration as well as on electromagnetic properties of irradiated samples. For metals optical radiation penetration length is usually rather small. For this reason and because of high values of metal thermal conductivity appearance of explosive (volume) boiling in metals irradiated with intense electromagnetic pulses is not evident beforehand in usual continual description of laser-metal interaction which is briefly depicted below. Steady state equation for temperature distribution $T(z)$ in evaporated sample (Al) (halfspace $z > 0$) has a form [1]:

$$\begin{aligned} & V\frac{\partial T}{\partial z} + \chi\frac{\partial^2 T}{\partial z^2} + \frac{\alpha I}{\rho c}\exp(-\alpha z) = 0 \\ & c\chi \left.\frac{\partial T}{\partial z}\right|_0 = LV, \\ & T(t,\infty) = T_\infty \end{aligned} \tag{1}$$

where the density ρ, heat capacity c, thermal diffusivity χ and absorption coefficient α are assumed to be constant. From (1) it follows:

$$\begin{aligned} & T_{st} = T_\infty + \Delta T\left[A\exp(-\alpha z) + B\exp\left(-\frac{V}{\chi}z\right)\right], \\ & A = V\left(c\Delta T + L\right)/\left(c\Delta T\left(V - \alpha\chi\right)\right), \\ & B = 1 - A, \quad \Delta T = T_0 - T_\infty \end{aligned} \tag{2}$$

$$I = \rho V(L + c\Delta T) \tag{3}$$

Vaporization velocity V and heat of evaporation L depend on surface temperature T_s:

$$V = 0.83\frac{p}{\rho_0}\sqrt{\frac{m}{2\pi k T_s}}, \quad p(T_s) = p_b \cdot \exp\left(11.5 \cdot (1 - T_b/T_s)\right) \tag{4}$$

where p — saturation pressure at surface temperature T_s, $T_b = 2792\,\mathrm{K}$ is normal boiling temperature, $p_b = 1\,\mathrm{bar}$, m — mass of the evaporated particles, k is Boltzmann constant

Figure 1 shows temperature distributions $T(z)$ for two different intensities and $\alpha = 0.7 \cdot 10^6\,\mathrm{cm}^{-1}$. The distributions demonstrate that the surface temperature T_s is somewhat lower then the maximum temperature T_m. For metals with high values of α and χ relation $(T_m - T_s)/T_m \ll 1$ is rather small even at high temperatures where V approaches its maximum value. For this reason in some papers [2, 3] it is argued that this difference can be neglected. However, our recent investigations [4–6] show that it is this temperature difference which gives rise to explosive (volume) boiling in the subsurface region where additional subsurface superheating occurs.

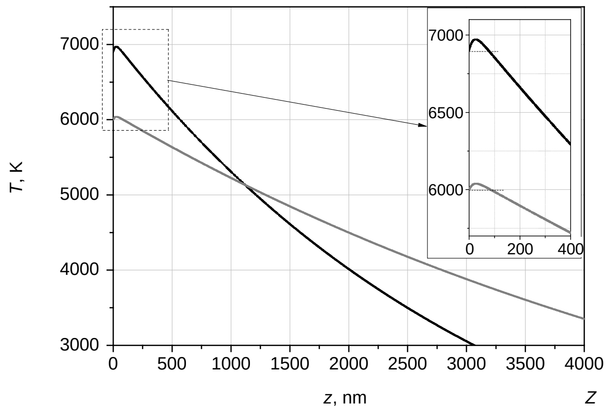

Figure 1: Temperature distributions $T(z)$ for two intensities: $I = 19.5\,\mathrm{MW/cm^2}$ (gray curve), $I = 38.5\,\mathrm{MW/cm^2}$ (black curve).

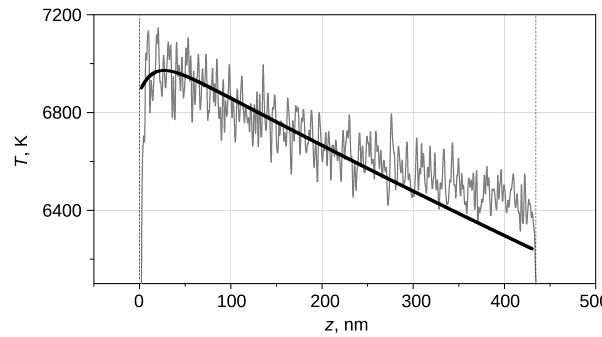

Figure 2: Comparison of temperature distributions from MD calculations (fluctuating curve) just before explosive boiling and from Stefan-like model (1) for $I = 38.5\,\mathrm{MW/cm^2}$.

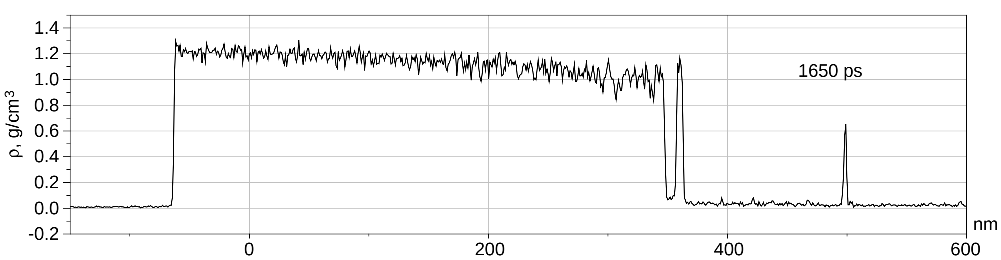

Figure 3: 1D particle density distribution at $t = 1650\,\mathrm{ps}$ after the radiation pulse with constant intensity $I = 38.5\,\mathrm{MW/cm^2}$ is switched on.

Using molecular dynamic (MD) simulations combined with continual description of metal electron subsystem we analyze nanosecond laser pulse action on metal (Al) film targets with 48 and 430 nm thickness which are initially in liquid states with temperature 6400 K. For this model critical parameters are 7600 K, $0.48\,\mathrm{g/cm^3}$ and 1.4 kbar.

Four different ablation regimes are observed depending on electromagnetic pulses intensities: surface evaporation which can be described in the framework of Stefan-like model (1), explosive (volume) boiling, spinodal decomposition and supercritical fluid expansion [4–6]. At shorter (picosecond) pulses spallation effect (see, e.g., [7, 8]) due to negative pressure values generated in the thin film is also observed.

Temperature distributions obtained from MD and from Stefan-like analytical model are shown in Figure 2 with the same value of $T_s = 6900\,\mathrm{K}$ and others parameters as in Figure 2 at $I = 38.5\,\mathrm{MW/cm^2}$. Right-side temperature deviation is due to finite thickness of the film as compared with halfspace analytical model (1) while at the left side there is a satisfactory agreement between MD and analytical modeling. However in Stefan-like (1) description of laser ablation there is no information on fluctuation behavior which becomes unstable at the superheating limit and initiates explosive boiling process.

As it was already mentioned above appearance of explosive (volume) boiling in metals irradiated with intense electromagnetic pulses is not evident beforehand because of high values of thermal conductivity and small radiation penetration length. Nevertheless, the explosive boiling process at absorbed radiation intensities $I = 38.5$ and $44\,\mathrm{MW/cm^2}$ is clearly visible in 1D (Figure 3) and 2D (Figure 4(a)) particle density distributions, respectively (in Figures 3–5 the film is irradiated from the right, z-axis is normal to the film surface).

Explosive boiling process at the considered intensities repeats itself several times. At $I = 38.5\,\mathrm{MW/cm^2}$ 5 explosion are observed during 2.4 ns pulse duration. Figure 3 shows 1D particle density distribution at $t = 1650\,\mathrm{ps}$ just after the third explosion (at 1640 ps). The result of the second explosion is also visible in Figure 3 as a smaller density peak.

Figure 4(a) shows several flying away target fragments formed after explosions at earlier moments

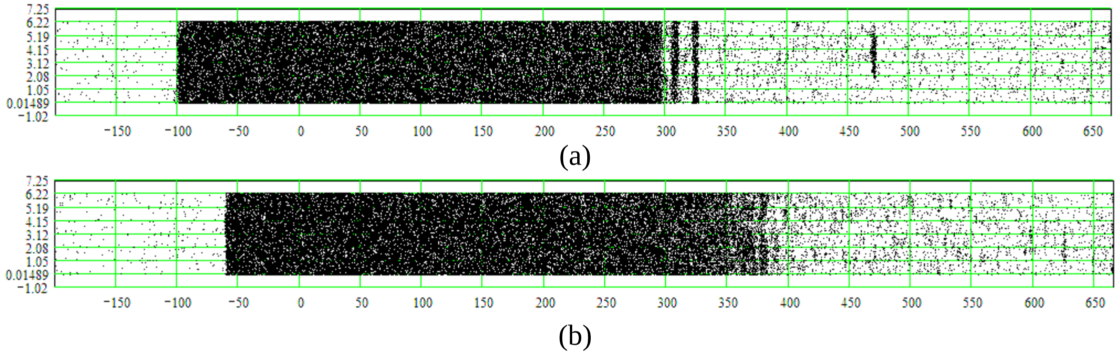

Figure 4: 2D snapshots of particle density, (a) at $t = 1.82$ ns after the radiation pulse with constant intensity $I = 44\,\mathrm{MW/cm^2}$ is switched on, and (b) at $t = 0.73$ ns with $I = 88\,\mathrm{MW/cm^2}$.

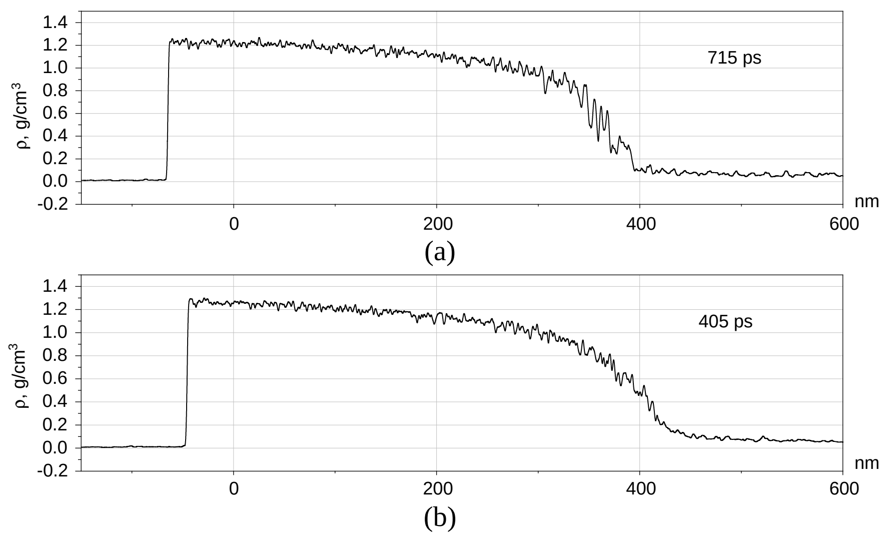

Figure 5: 1D particle density distributions at (a) $t = 715$ and (b) 405 ps after the radiation pulse with constant intensities $I = 88$ and $154\,\mathrm{MW/cm^2}$ are switched on, respectively.

1.16 ns, 1.5 ns and 1.79 ns. Remnants of the first fragment which was formed due to the first explosion at 0.71 ns are not visible here.

The fragments with initially well defined boundaries then become thinner and disintegrate due to surface evaporation process. Figure 4(b) and Figure 5(a) show spinodal decomposition regime where density fluctuations have no such distinct boundaries as in the explosive boiling case. In contrast to the explosive boiling and spinodal decomposition regimes which occur at subcritical pressure and temperature values with considerable fluctuations, in supercritical expansion regime (Figure 5(b)) the fluctuation are not so prominent.

Initial thickness of the explosive boiling fragment is of the order of radiation penetration length (about 10 nm). This result means, in particular, that in theoretical description of the explosive boiling process in irradiated metals [2, 3] it is necessary to take properly into account finite value radiation penetration length.

Pressure pulses with about two hundreds bar amplitude and two hundreds ps duration generated during explosive boiling [5] can be used as markers of critical region approaching as it was suggested four decades ago [9].

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