HYDRODYNAMIC REGIME OF LASER ABLATION OF METALS
BY ULTRASHORT PULSES OF LOW FLUENCE

Yu. V. Afanasiev, B. N. Chichkov, N. N. Demchenko, V. A. Isakov, and I. N. Zavestovskaya

P. N. Lebedev Physical Institute, Russian Academy of Sciences, Leninskii Pr. 53, Moscow 117924, Russia
e-mail: isakov@sci.lebedev.ru demch@neur.lpi.msk.su

Abstract

Metal ablation taking into account the hydrodynamics of a dense ablated material with ion temperature close to critical is considered. An extended two-temperature model taking into account hydrodynamic plasma expansion and degeneracy of the electron gas is developed. The new version of the RAPID code is used to perform calculations of ablation rates for several metal targets under conditions where the electron degeneracy is important.

1. Introduction

The definition of the threshold fluences in the problem of laser ablation of metals by pico- and femtosecond pulses [1, 2] assumes that at low laser fluences $F$, close to the ablation threshold $F_{th}$, the thermal mode is the dominant ablation mechanism [3]. This means that the ablation is determined by the heating of the electron gas due to thermal conductivity followed by electron-ion relaxation providing the heating of the lattice. Thus, the problem can be formulated within the framework of the two-temperature model [4]. The heated region inside the metal is considered as motionless, and the ablation rate (the ablation depth per pulse $d$) depends only on the time evolution of the surface ion temperature. The value $d$ is connected with evaporation in vacuum [5] and can be determined by the integral [3]

$$d \approx \frac{b}{(2\pi)^{1/2}} \int_0^\infty \left[ \frac{T_i(t)}{m_i} \right]^{1/2} \exp \left[ -\frac{U_0}{T_i(t)} \right] dt,$$

where $m_i$ is the lattice ion mass, $T_i(t)$ is the surface lattice (ion) temperature (here and below the temperature is written in energy units), $U_0$ is the bond energy, and $b \approx 10^3$ is a dimensionless parameter. Such a problem was solved in [3], where analytical expressions for the threshold laser fluences $F_{th}$ and the surface ion temperature $T_i(F_{th}, t) = T_i^{th}(t)$ were obtained as functions of typical metal parameters.

Nevertheless, the surface evaporation and the corresponding integral expression for ablation depth are valid if the surface temperature $T_i(t)$ is lower than the critical temperature of the metal $T_{cr} \approx (0.1 - 0.2)U_0$ [6]. According to [3] the maximum ion temperature 0.41 eV corresponding to the ablation threshold $F_{th}$ \approx 90 mJ/cm$^2$ in Au can be comparable to the critical temperature. Certainly, the surface ion temperature becomes critical for $F \geq F_{th}$. It is clear that, in general, for laser fluences close to the ablation threshold the surface evaporation approach is irrelevant and the hydrodynamic motion of the dense heated material should be taken into account.

In the present paper we consider metal ablation taking into account the hydrodynamics of the ablated material whose density is close to the metallic one and whose lattice temperature $T_i \approx T_{cr}$. Such an approach is an extended two-temperature model of the metal.
2. Formulation of the Problem

The physical model of ablation is based on the equations of two-liquid hydrodynamics for electrons and ions taking into account degeneracy of the electron gas and the Maxwell equations for absorption of laser radiation [7].

The system of hydrodynamic equations is of the Lagrangian form

\[
\frac{\partial V}{\partial t} = \frac{\partial u}{\partial m},
\]

\[
\frac{\partial x}{\partial t} = u,
\]

\[
\frac{\partial u}{\partial t} = -\frac{\partial}{\partial m} \left( p_{\tau_e} + p_i \right) ,
\]

\[
\frac{\partial \varepsilon_{\tau_e}}{\partial t} = -p_{\tau_e} \frac{\partial V}{\partial m} - \frac{\partial q_{\tau_e}}{\partial m} - \frac{\partial q_L}{\partial m} - Q_{ei}(T_e - T_i),
\]

\[
\frac{\partial \varepsilon_i}{\partial t} = -p_i \frac{\partial V}{\partial m} + Q_{ei}(T_e - T_i),
\]

where \( V = 1/\rho, \rho, \) and \( u \) are the specific volume, density, and velocity of the evaporated material, \( x \) and \( m = \int \rho \, dx \) are the Eulerian and Lagrangian coordinates, \( T_e \) and \( T_i \) are the electron and ion temperatures, \( p_{\tau_e} \) and \( p_i \) are the thermal electron and ion pressures, \( \varepsilon_{\tau_e} \) and \( \varepsilon_i \) are the specific internal energies of the electron and ion subsystems, \( q_{\tau_e} \) is the electron heat flux density, \( q_L \) is the laser flux, and \( Q_{ei} \) is the electron–ion relaxation coefficient.

The model under consideration assumes that the metal consists of electroneutral atomic cells with nuclei in the center. The thermodynamic functions of ions (pressure and internal energy) are connected with the movement of the whole cell, whereas the thermodynamic functions of electrons are determined by the state of electrons in the cell. The later is considered within the approach of the uniform electron gas [9], i.e.,

\[
p_{\text{ueg}} = 1.6 \cdot 10^{-12} n_e T_e \left[ 1 + \frac{0.706 \cdot 10^{-22} n_e}{T_e^{3/2}} + \frac{3.99 \cdot 10^{-45} n_e^2}{T_e^3} \right]^{1/3} \text{erg/cm}^2, \quad n_e = Z n_i,
\]

where \( n_e \) and \( n_i \) are the densities of free electrons and ions, \( [n_e] = [n_i] = \text{cm}^{-3} \), and \( [T_e] = \text{eV} \). For \( T_e \gg (3.99 \cdot 10^{-45} n_e^2)^{1/3} \) expression (2) corresponds to an ideal electron gas and in the opposite case – to a degenerate electron gas.

The thermal electron pressure can be extracted from \( p_{\text{ueg}} \) in the following way [9]:

\[
p_{\text{ueg}}(n_e, T_e) = p_{\tau_e}(n_e, T_e) + p_{\text{ueg}}(n_e, 0).
\]

Strictly speaking, Eqs. (2) and (3) are valid either for high temperature or high electron density where the kinetic energy of electrons is much higher than their potential energy and all electrons are free. This means that \( Z \) in Eq. (2) should be equal to the nucleus charge. Nevertheless, within the phenomenological model under consideration \( Z \) is used as a fit parameter. Applicability of the model is verified by comparison with experimental data.

Further, the thermal energy of the electron gas and the pressure and internal energy of ions are assumed to be determined by

\[
\varepsilon_{\tau_e} = \frac{3 p_{\tau_e}}{2 \rho},
\]

\[
p_i = p_{\tau_i} + p_{\text{cold}},
\]

\[
\varepsilon_i = \varepsilon_{\tau_i} + \varepsilon_{\text{cold}},
\]

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