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Transient effects in pulsed laser irradiation

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Abstract

Theoretical analysis of the influence of the temporal profile (rectangular, triangular, Gaussian) of the laser pulse on heating/cooling and phase transition velocities and quantity of ablated material was performed on the basis of a multifront Stephan problem. Modeling showed that material removal under stationary conditions (that correspond to long pulses) is entirely controlled by specific heat and material density, while in the case of transient regimes (short pulses) thermal conductivity and heat capacity play a predominant role. Interaction of the melting and evaporation fronts characterized by an evaporation front velocity far exceeding the melting front one is one of the examples of the transient nature of the phenomena influenced by the laser pulse parameters.

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Keywords: Laser melting; Laser evaporation; Laser pulse shape

1. Introduction

Most of the technological thermal processes of laser treatment of materials are concerned with the first order phase transitions: melting–solidification and evaporation–condensation. The role of the relationship between the depth of the molten pool and the thickness of the evaporated layer is critical in drilling, pulsed cutting and welding. In these processes the size of the molten pool and geometry of the hole depend on both laser irradiation parameters defined by wavelength, pulse duration and time-space distribution of pulse intensity, as well as thermophysical and optical properties of the treated material [1]. To optimize a chosen technological application, the influence of each of these factors must be analyzed and characterized. Fulfilling this task requires modeling of the time-space distribution of temperature fields and the phase transition dynamics. In this purpose a number of mathematical models have been used [2,3].

The published results [4–6] demonstrate a significant role of the transient effects in laser processing. Nevertheless, although a great number of publications consider various issues of laser irradiation, the issue of transient effects is far from being completely studied.

The aim of the present paper is to analyze the transient effects in a wide range of pulse durations and intensities in laser processing of metals with strongly different thermophysical properties such as copper and titanium.

2. Formulation of the problem

Processes of laser heating, melting and evaporation of metals are described in the frame of a joint variant of the Stephan problem including the classical and one-phase approaches [3]. This joint model solves the thermal conductivity equation with boundary conditions at two moving interphases $\Gamma_{sl}(t)$ (solid–liquid) and $\Gamma_{lv}(t)$ (liquid–vapor). Their location is a priori unknown and found in the course of solution through the corresponding boundary conditions. The absorbed laser radiation is assumed to be released in the thin surface layer. The origin of the coordinate frame is situated at the surface of the irradiated target, thereby the melting velocity is directed inwards and thus negative. Consequently, the solidification velocity is positive.

Numerical solution of the system of equations is carried out using a dynamical adaptation [7,8] allowing to explicitly track the phase boundaries.

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Two metals with strongly different thermophysical properties were used as target: copper with high thermal conductivity and titanium with low thermal conductivity and high heat of fusion [9,10]. The difference is most pronounced for thermal conductivity which is 10 times higher for copper and for the value of specific heat of vaporization L_v which is 3 times higher for titanium. Absorption of the metallic surface was assumed independent of the temperature and given as $A = 0.1$ that corresponds approximately to the absorption of the polished metals at the $\lambda_l \approx 10.6$ μm laser radiation.

3. Analysis of the modeling results

Generated by a single laser pulse, a number of sequentially emerging nonlinear processes constitute the dominating mechanism for mass and energy transfer in the irradiation zone. The final result of these competing processes is controlled by a number of laser irradiation parameters. One of them is the energy input rate defined by the temporal profile of the laser pulse. The largest difference in material processing is supposed to be between the cases characterized by a transient energy input (i.e. single pulse) and by those with a steady energy input that, provided a sufficient duration, could establish stationary conditions.

The one-dimensional steady-state evaporation is characterized by the energy balance equation [11]:

$$x = \Gamma_{lv}(t) : G_{sur} = AG = \rho_l \upsilon_{lv}\left(L_m + L_v + \int_{T_0}^{T_{sur}} C_p(T)\,dT + \sigma T_{sur}^4\right), \quad (1)$$

The velocity of the evaporation front υ_{lv} may be given as the following approximated equality:

$$\upsilon_{lv} = \frac{G_{sur}}{\rho_l L_v} \approx \upsilon_0 \exp\left(-\frac{L_v}{kT_{sur}}\right) \quad (2)$$

where υ_0 is a velocity close to the sonic velocity in metal, G_{sur} is the absorbed radiation intensity, ρ_l is the density of the liquid state, C_p is the heat capacity, L_v, L_m are the specific heat of vaporization and melting, k is the Boltzmann constant, σ is the Stefan Boltzmann constant.

3.1. Influence of the temporal profile of the laser pulse

Let us analyze heat and mass transfer dynamics between the vapor, liquid and condensed phases for pulses with different temporal profiles but the same energy input and duration.

3.1.1. Rectangular pulse

The rectangular temporal profile, Fig. 1a, $G = \begin{cases} G_0, t \le \tau_1 \\ 0, t > \tau_1 \end{cases}$, was chosen as reference for the others. The absorbed intensity was $G_{sur} = 10^7$ W cm^{-2}, the pulse duration was $\tau_1 = 2 \times 10^{-4}$ s. The values of intensity $G(t)$ and pulse duration τ_1 were selected in such a way to make it possible for the system to reach a steady state in terms of both surface temperature T_{sur}, Fig. 2 and phase boundaries velocities $\upsilon_{sl}(t)$, $\upsilon_{lv}(t)$, Fig. 3.

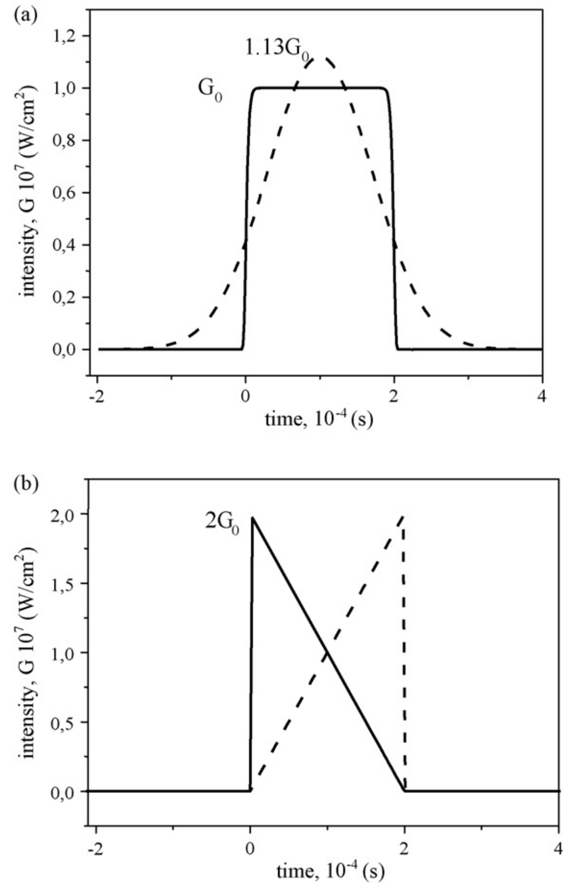

Fig. 1. Pulse temporal profiles: (a) rectangular and Gaussian, (b) right-angled triangular with increasing (rising triangle) and decreasing (falling triangle) energy density fluxes.

A particularity of the rectangular-pulse irradiation is the presence of two transient intervals related to instantaneous changes in intensity, namely the fore and the rear fronts corresponding to the switch-on and the turn-off of the pulse. A jump-like change in intensity at the switch-on of the pulse leads to the formation of a near-surface zone of the maximum temperature gradients. The comparison (Table 1) of the

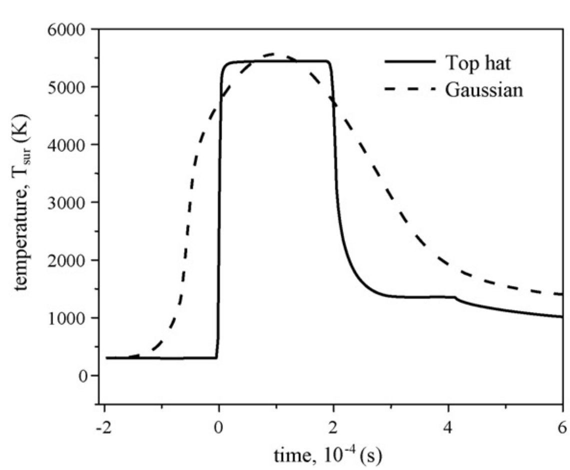

Fig. 2. Evolution of the surface temperature $T_{sur}(t)$ for copper: rectangular (full line) and Gaussian (dashed lime) pulses.