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Micromachining of copper by femtosecond laser pulses

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ABSTRACT

Simulation results of femtosecond laser ablation of copper were compared to experimental data. The numerical analysis was performed using a predictive model, including a two temperature model, an optical critical point model with three Lorentzian terms, two phase change models for melting and evaporation under superheating, and a phase explosion criterion for ejection of metastable liquid decomposing into droplets and vapor phase. The experiments were conducted with a 120-fs, 800-nm Ti:sapphire lasers for fluences up to 408 J/cm^2. The ablation depths were measured, and the ablation rate was estimated. It was shown that the present numerical simulations correlate well with the experimental data over the entire range of the laser fluences investigated except for those below 0.8 J/cm^2, indicating that the proposed model is an accurate and efficient tool for predicting ultrashort-pulsed laser material ablation.

1. Introduction

Femtosecond laser material processing has been demonstrated as a very effective means for micro/nano machining and surface modification of solid materials due to minimal heat affected zone, less debris contamination, and good reproducibility. Two types of the material removal mechanisms are often categorized: thermal ablation and non-thermal ablation. The former includes ultrafast phase changes through melting and vaporization as well as phase explosion if laser fluences are sufficiently high, while the latter is caused by thermal stresses, coulomb explosion, and/or hot electron blast when the laser is operated at fluences slightly exceeding the ablation threshold. Although the non-thermal ablation can precisely process materials with minimal damage, it suffers from its slow process due to low laser fluence. This therefore creates a need for developing a more efficient processing approach. One potential means, for example, is to process a material target by irradiating high-fluence laser pulses and then followed by relatively low-fluence pulses.

An intensive number of theoretical investigations on ultrashort-pulsed laser interactions with matter have been reported since early 1990s. Most of them are focused on fundamental thermal transport using a two-temperature model (TTM) [1–3]. Different approaches are also proposed to simulate material ablation, including ultrafast thermoelasticity [4], dynamics of thermal ablation [5,6], hydrodynamic modeling [7,8], molecular dynamics [9,10], etc. Only few typical papers are cited here since this is not a review paper. The laser fluences considered so far have been up to several tens J/cm^2. Due to the extreme complicity of the physics involved in the entire ablation process as well as a lack of well-quantified thermophysical and optical properties, none of them can precisely predict the ablation process over the whole range of laser fluences. To optimize the ultrashort-pulsed laser material process, further efforts for comprehensive understanding and accurate description of ultrafast thermal transport behavior and material ablation response are necessitated [5,6,8,11].

In this paper, experimental and numerical results are reported on femtosecond laser ablation of copper. The laser experiments are performed to obtain ablation depth for fluences up to 408 J/cm^2. The numerical analysis is carried out using a predictive model including a TTM, two phase change models for melting and evaporation under superheating, and a phase explosion criterion for ejection of metastable liquid decomposing into droplets and vapor phase. Together with an electron ballistic range, the laser energy deposition is described with temperature-dependent optical properties obtained from a critical point optical model with three Lorentzian terms. All the material properties employed in the model simulations are suited for a wide range of temperatures. The numerical results and the experimental data are compared and discussed.

2. Experiment

A commercial copper foil (GTJ-MP, FCFT) of thickness 35 μm is machined in air by an 800 nm wavelength regenerative amplified

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mode-locked Ti:sapphire laser (SPITFIRE, Spectra-Physics) operated at a repetition rate of 1 kHz. The pulse duration is ~120 fs, and the maximum available pulse energy is ~3.5 mJ. The laser beam is linearly polarized and spatially filtered, resulting in an essentially Gaussian profile. The energy of the laser beam is attenuated by a rotatable half-waveplate and a polarizing beam splitter. The transmitted component of the laser beam is incident onto a beam splitter, the reflected beam is directed to a power detector, and the laser irradiation energy on the copper target is measured. Meanwhile, the transmitted linearly polarized laser beam is passed through a shutter and a series of reflective mirrors, and subsequently entering an objective lens (numerical aperture 0.26, M Plan Apo NIR, Mitutoyo). The position of the objective lens is adjusted in the vertical direction (i.e. *Z*-axis). Grooves are machined by translating the target sample using an *X*–*Y* motion stage at a line scanning speed of 0.5 mm/s. The laser process is continuously monitored via a co-axis charge-coupled device (CCD) camera system. The morphology of the grooves is measured using a scanning electron microscopy (SEM, Hitachi S-4700). The copper foil samples are sectioned and polished, and the width and depth of the grooves are measured from the top view and cross section SEM images, respectively. The laser powers applied to machine the grooves are in the range of 0.0014 W–0.14 W.

3. Modeling and simulation

To accurately simulate the thermal ablation process, a set of physical models are needed, including a TTM for electron temperature (T_e) and lattice temperature (T_l) [1,3], two phase change models [12] for melting and evaporation under superheating, a hydrodynamic model for liquid [8] and vapor motion, and a phase explosion model for ejection of metastable liquid decomposing into droplets and vapor phase [5,13]. Besides the above thermal models themselves, an optical model that is able to characterize temperature-dependent surface reflectivity (R) and absorption coefficient (α) is of paramount importance because these two optical properties dictate laser energy deposition that can significantly alter the simulation result of the thermal response and material ablation [8,14]. The above models are briefly discussed in the following except for the hydrodynamic model that is not taken into account in the present study.

3.1. Two-temperature model

Consider that a free standing copper foil of thickness L and at initial temperature T_i is normally irradiated by a femtosecond laser pulse of fluence J_o on the front surface ($x = 0$). The laser pulse is Gaussian in time with a full width at half maximum (FWHM) t_p. For simplicity without losing accuracy, the problem is approximated to be one dimensional since the laser spots are much larger than the thermal affected depth. The one-dimensional TTM for electron and lattice temperature in a copper foil is expressed as follows [3]:

$$C_e\frac{\partial T_e}{\partial t} = \frac{\partial}{\partial x}\left(k_e\frac{\partial T_e}{\partial x}\right) - G(T_e - T_l) + S \tag{1}$$

$$C_l\frac{\partial T_l}{\partial t} = \frac{\partial}{\partial x}\left(k_l\frac{\partial T_l}{\partial x}\right) + G(T_e - T_l) \tag{2}$$

where C is heat capacity, k thermal conductivity, G electron-phonon coupling factor, and S laser heat density. The subscripts e and l are associated with electrons and lattice, respectively. Thermal conductivity of lattice is usually neglected in the TTMs for pure metals due to the fact that it is two orders smaller than that of electrons. However, the heat conduction in the lattice should be considered in this model for which it includes solid–liquid (S–L) and liquid–vapor (L–V) phase change.

The laser heat density S in Eq. (1) is written in the form:

$$S(x,t) = 0.94\frac{[1-R(0,t)]J_o}{t_p}\frac{1}{\delta(x,t)+\delta_b}\exp\left[-\int_0^x\frac{1}{\delta(x,t)+\delta_b}dx - 2.77\left(\frac{t}{t_p}\right)^2\right] \tag{3}$$

where t denotes time, $\delta = 1/\alpha$ is the optical penetration depth, and δ_b is the electron ballistic range. The surface reflectivity R and absorption coefficient α are temperature dependent. The electron ballistic range added to the optical penetration depth here is to take into account the effects of the ballistic motion and hot electron diffusion that spreads the absorbed laser energy into a deeper part of electrons, especially for the s/p-band metals [15].

3.2. Optical model

To match experimental data of ultrashort laser material ablation, either a surface reflectivity constant R [5,6] or an absorbed laser fluence J_{abs} [11] together with a constant α at room temperature are often assumed for laser energy deposition. The inadequacy of those semi-empirical approaches is that the values of R or J_{abs} may be case dependent and need to be re-selected, through trial and error, when the laser heating conditions are changed. Other approaches [8,16] are to solve the electromagnetic wave equation, and the laser energy deposition is then deduced using the Joule–Lenz law.

Recently, Ren et al. [14] showed that the critical point model [17] with three Lorentzian terms can accurately characterize surface reflectivity and absorption coefficient of copper for a wide range of laser wavelengths 200–1000 nm. In view of its simplicity, this optical model is adopted in this work. The expression of the critical point model with three Lorentzian terms is given as:

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_D^2}{\omega^2 + i\gamma\omega} + \sum_{p=1}^{3} B_p\Omega_p\left(\frac{e^{i\phi_p}}{\Omega_p - \omega - i\Gamma_p} + \frac{e^{-i\phi_p}}{\Omega_p + \omega + i\Gamma_p}\right) = \varepsilon_1(x,t) + i\varepsilon_2(x,t) \tag{4}$$

where ε_∞ is dielectric constant, ω_D plasma frequency, ω laser frequency, γ damping coefficient which equals reciprocal of electron relaxation time (τ_e), B a weighting factor, and Ω, ϕ and Γ energy of gap, phase and broadening, respectively.

The optical properties R and α can be obtained from Fresnel function [18]:

$$R(x,t) = \frac{(f_1(x,t)-1)^2 + f_2^2(x,t)}{(f_1(x,t)+1)^2 + f_2^2(x,t)} \tag{5}$$

$$\alpha(x,t) = \frac{2\omega f_2(x,t)}{c} \tag{6}$$

where c is light speed in vacuum, and the normal refractive index f_1 and extinction coefficient f_2 are functions of ε_1 and ε_2 in Eq. (4):

$$f_1(x,t) = \sqrt{\frac{\varepsilon_1 + \sqrt{\varepsilon_1^2+\varepsilon_2^2}}{2}} \tag{7}$$

$$f_2(x,t) = \sqrt{\frac{-\varepsilon_1 + \sqrt{\varepsilon_1^2+\varepsilon_2^2}}{2}} \tag{8}$$

The electron relaxation time, which is the reciprocal of damping coefficient γ in Eq. (4), is often taken as $\tau_e = (A_l T_l + A_e T_e^2)^{-1}$. The first term in the parenthesis represents the phonon–electron