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Analysis of removal region in nanoscale metal film processed by ultrafast-pulse laser

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ABSTRACT

The ultrafast-pulse laser can be employed for the micromachining of nanoscale optical and electronic devices due to hardly diffusive heat-induced zone in very short period. In order to effectively control the processing quality, the ultrafast-pulse laser with certain wavelength and absorptivity for material is preferred. The processing characteristics of nanoscale devices patterned by ultrafast-pulse laser are different from these of traditional large scale device and long pulse laser. The traditional model cannot correctly account for processing characteristics. Therefore, this study utilizes an improved electron kinetic theory to analyze the processing characteristics of the nanoscale metal film ablated by ultrafast-pulse laser. The ablated depth per pulse and crater diameter in nanoscale metal film are predicted by this work and compared with the available measured data. This study theoretically validates that the first regime is determined by directly optical penetration absorption for low laser fluences and the second regime is governed by the thermal diffusion for high laser fluences. The effects of material properties on the ablation rate and squared diameter are also discussed.

1. Introduction

The laser with a certain wavelength has its benefits in machining applications. These benefits include the control of the material energy absorption for laser in the machining process. The material energy absorption for laser is one of key factors in materials processing efficiency and quality. The light amplification by stimulated emission of radiation can induce the concentrated and unidirectional high-intensity energy beam which is powerful tool for material processing. Ultrafast pulse laser has very short time irradiating material. When the duration of an ultrafast pulse laser is comparable to or shorter than the electron mean free time (in the order of 1 ps), the pulse laser transferring energy into electrons has already disappeared before the excited electrons transfer thermal energy into the lattices. Electron temperature rise due to low specific heat capacity of the electrons and short relaxation time. Thermal nonequilibrium occurs between the excited electrons and the undisturbed lattices. This phenomenon makes it be possible that sharp well-defined microstructures can be produced in the absence of the liquid phase molten material and with a minimum thermal and mechanical damage.

The ultrafast-pulse light amplification by stimulated emission of radiation has many applications in materials processing [1–4]. Especially for an ultrashort-pulse laser [5–10], its rapid advance has opened up new possibilities of micromachining. It had been shown that femtosecond pulsed laser ablation has significant advantage over conventional laser machining. The special technology of femtosecond laser ablation for materials gives a possibility to machining nanoscale structures. In order to analyze the micro- and nano-machining mechanisms of the femtosecond laser ablation for materials, nanoscale thermal transport models were employed to investigate the nonequilibrium heat transfer in thin metallic film [11–23] and the measurement of the femtosecond laser ablation for metal film was executed [24–26].

Laser ablation based on the vaporization of materials can generate the narrow and deep microstructure due to the small local heat spot and high intensity energy of laser beam [27–29]. On the whole, the femtosecond laser ablation can prevent large heat-affected region in the machining target, which was difficultly achieved with longer laser pulses [29]. Compared with the picosecond laser pulse, the femtosecond laser pulse can induce

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non-thermal material removal owing to electronic excitation [27]. Femtosecond laser had been employed as the accurate materials machining tool due to very small heat-affected zone in the material [30,31].

With the quick progress in microelectronic and optoelectronic devices, the laser machining for thin films has increasingly attracted attention due to noncontact and large region technique. As thin film thicknesses diminish from micrometers to nanometers, the size effects on the energy transportation become significant [32]. When the heat conduction model based on Fourier law was utilized to analyze the energy transport in nanoscale thin films, the model can lead to the underestimated temperature rises.

Femtosecond laser machining for materials is a powerful technique for achieving micro- and nanostructures due to minimal thermal defects and collateral damage, less fragment contamination, and good reproducibility [33]. For ultrashort pulse laser processing for metallic materials, the Fourier's law, which suppose that the energy is transferred to the lattice by infinite speed, give the high lattice temperatures, lower electron temperatures, and smaller thermal defects [34]. Therefore the two-temperature model, which considers the nonequilibrium and finite time energy transfer between the lattice and electron, was proposed by Chen et al. [18] and Anisimov [35].

For femtosecond laser machining for materials, some materials ablating factor such as the Coulomb blast and vaporization may occur simultaneously or transfer sequentially in the ablation process [34]. Although two-temperature model, with the condition that the vaporization was the material removal factor, was applicable to analyze the femtosecond laser ablation for metal [36], the detailed phenomena in the femtosecond regime are still not revealed thoroughly. Specially, the effects of material properties and machining parameters on the femtosecond laser ablation for metals are not completely known yet. In order to understand these effects, the investigation into the femtosecond laser ablation for metals will be further conducted.

This study employed the improved electron kinetic theory with the vaporization as a removal mechanism to analyze the effects of material properties on the ultrafast-pulse laser ablation for metal film. The ablated depth and squared opening diameter per pulse are calculated and compared with the available measured data. The effects of material properties on the depth and opening diameter ablated by the ultrafast-pulse laser are also discussed.

2. Analysis

2.1. Thermal transport in ultrafast process and ultrasmall scale

The relaxation time scale in which the electrons transport thermal energy to the lattice is on the order of a picosecond for metals. When the period of ultrashort pulse laser heating of metal films is on the order of or shorter than a picosecond, a significant nonequilibrium can take place between the lattice and electron temperature because of the smaller heat capacity of electrons than that of phonons by two or three orders of magnitude. In the meantime, electrons are excited to a very high temperature in several tenths of picoseconds and the metal lattice only experiences a minimal increase of temperature or even stays almost thermally undisturbed.

In the ultrafast process or nanoscale where the particle description of electrons and phonons is valid for the boundary and interface scattering and the finite relaxation time of heat carriers, An improved electron kinetic theory [37] for transport in heat carriers is proposed to elucidate the thermal nonequilibrium between electrons and phonons when the laser pulse duration is smaller than the relaxation time of the energy carriers. The one-dimensional improved electron kinetic theory is written as

$$\left[\left(1+\tau_s\frac{\partial}{\partial t^*}\right)-\frac{\partial}{\partial x}\left(\frac{P_e^2}{f}\frac{\partial}{\partial x}\right)\right]C_l\frac{\partial T_l}{\partial t^*} = \frac{\partial}{\partial x}\left(k\frac{\partial T_l}{\partial x}\right)+\tau_p\frac{\partial}{\partial t^*}\left[\frac{\partial}{\partial x}\left(k\frac{\partial T_l}{\partial x}\right)\right]+\left\{I(t^*)+\tau_p\frac{\partial[I(t^*)]}{\partial t^*}\right\}\alpha f e^{-\alpha x} \quad (1)$$

In the left-handed side of Eq. (1), the first two terms represent the temperature change with time and the delay of the heat flux which leads to the finite speed of heat propagation and wave characteristics. The time derivative of diffusion results from the delay of temperature gradient. On the other hand, the first and third terms in the right-handed side of Eq. (1) represent the thermal diffusion and heat source, respectively. The similar terms such as time derivative of diffusion, thermal diffusion and the heat source terms are also appear in the dual-phase-lag model [38]. The temporal distribution function of the ultrafast-pulse laser can be written as

$$I(t^*)=\sqrt{\frac{4\ln 2}{\pi}}\frac{(1-R)J}{t_p}e^{-4\ln 2\left(\frac{t^*}{t_p}\right)^2} \quad (2)$$

and

$$I(t^*)+\tau_p\frac{\partial[I(t^*)]}{\partial t^*}=\sqrt{\frac{4\ln 2}{\pi}}\frac{(1-R)J}{t_p}e^{-4\ln 2\left(\frac{t^*}{t_p}\right)^2}\left[1-\frac{8\tau_p}{t_p}\left(\frac{t^*}{t_p}\right)\ln 2\right] \quad (3)$$

where τ_s is the electron–phonon characteristic time ($\tau_s = C_e/G$), G is the electron–phonon coupling factor, P_e is the mean free path of the electrons, f is the fraction of excess energy change, C_l and C_e are the lattice and electron heat capacities, respectively, k is the thermal conductivity, τ_p is the electron mean free time between electron–phonon coupling [37], α is the absorption coefficient, x is the coordinate toward the interior of the metal film, R is reflectivity, t_p is the duration of laser pulse defined as full width at half maximum (FWHM) of the pulse and t^* is the time variable. T_l and T_e are the lattice and electron temperatures, respectively.

According to the fraction of the electron–phonon coupling excess energy per unit area, the following equalities are introduced

$$\frac{f}{P_e^2}=\frac{C_e}{k\tau_s}=\frac{G}{k} \quad (4)$$

Therefore, Eq. (1) yields

$$\left[\left(1+\frac{C_e}{G}\frac{\partial}{\partial t^*}\right)-\frac{\partial}{\partial x}\left(\frac{k}{G}\frac{\partial}{\partial x}\right)\right]C_l\frac{\partial T_l}{\partial t^*} = \frac{\partial}{\partial x}\left(k\frac{\partial T_l}{\partial x}\right)+\tau_p\frac{\partial}{\partial t^*}\left[\frac{\partial}{\partial x}\left(k\frac{\partial T_l}{\partial x}\right)\right]+\left\{I(t^*)+\tau_p\frac{\partial[I(t^*)]}{\partial t^*}\right\}\alpha f e^{-\alpha x} \quad (5)$$

The nonequilibrium between electrons and lattice gradually approaches the equilibrium due to the rise rate of lattice temperature with time.

$$T_e=\frac{C_l}{G}\frac{\partial T_l}{\partial t^*}+T_l \quad (6)$$

For the case $C_e \ll C_l$, $\tau_p \ll \frac{C_l}{G}$, substitution Eq. (6) into Eq. (5) gives the improved electron kinetic theory of heat transport based on the electron temperature.

$$C_e\frac{\partial T_e}{\partial t^*}=\frac{\partial}{\partial x}\left(k\frac{\partial T_e}{\partial x}\right)-G(T_e-T_l)+\left\{I(t^*)+\tau_p\frac{\partial[I(t^*)]}{\partial t^*}\right\}\alpha f e^{-\alpha x} \quad (7)$$

In most of the investigations, the temperature-dependent thermal properties of thermal conductivity and heat capacity of electrons for gold have been widely used as $C_e = C_{e0}\left(\frac{T_e}{T_0}\right) = B_e T_e$ and $k = k_{eq}\frac{T_e}{T_l}$, respectively. C_{e0} is the heat capacity of electrons at room temperature T_0.