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Laser drilling of silicon nitride and alumina ceramics: A numerical and experimental study

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Laser drilling of silicon nitride (Si_3N_4) and alumina (Al_2O_3) ceramics targets was studied theoretically and experimentally. A one-dimensional model based on the heat-transfer equation was developed in order to describe the process. It includes a change of the type of the equivalent heat source during the laser pulse. The drilling of Si_3N_4 and Al_2O_3 ceramic slabs was performed by using a TEM_{00} *Q*-switched 10 ns pulse Nd:YAG laser. When the absorption of the plasma formed during the drilling process was taken into account, the theoretical results obtained agreed well with the experimental ones. [DOI: 10.1063/1.1334367]

I. INTRODUCTION

Laser micromachining and microstructuring has attracted a great deal of interest in recent years.[1,2] Among its advantages is the possibility machining hard and brittle materials that can be easily damaged by conventional drilling and cutting procedures. There is now a growing interest in laser micromachining using pulses of pico- and femtosecond duration.[2,3] It was shown experimentally that these pulses produce sharp and well-defined holes and cuts;[3] also, many works were devoted to the laser cutting of ceramic materials with such pulses—they demonstrated the formation of high-quality cuts and holes.[4,5]

Although material processing with laser pulses of nanosecond duration has been studied extensively for the case of metal and semiconductor targets,[6] the interaction of nanosecond pulses with ceramic targets still needs further investigation. In these materials, the phase transition from solid to vapor occurs without melting the material.[7] Another feature of the ceramics is the strong dependence of the thermophysical parameters on the grain size and material composition. These specific properties of the ceramics require more careful examination of the interaction of laser light with the samples. A number of numerical models have been developed dealing with laser processing of ceramic materials using cw[7,8] or pulsed lasers with laser pulse duration above 100 ns.[9,10] For shorter laser pulses, on the order of a few nanoseconds, a different drilling model should be used.

In this work, the laser drilling of silicon nitride (Si_3N_4) and alumina (Al_2O_3) ceramic plates was studied both theoretically and experimentally. A one-dimensional numerical model employing the heat transfer equation was used, which also accounts for the change of the equivalent heat source from that of volumetric to surface during the laser pulse. Moreover, the absorption of the plasma plume formed on the surface of the ceramics was taken into account, which resulted in good agreement between the experimental and theoretical results. The experiments were performed by using a TEM_{00}, 10 ns pulse Nd:YAG laser.

II. THEORETICAL BACKGROUND

A. The model

The drilling arrangement considered in the numerical model is shown in Fig. 1. The model is based on the following assumptions:

(1) The material evaporation occurs in a single step, i.e., the phase transition from solid to vapor occurs without melting.

(2) The ablation of the material surface takes place in a layer-by-layer way. When a particular layer reaches the evaporation temperature and the incoming energy exceeds the latent energy of evaporation for this layer, this part of the material is being removed and no longer considered.

(3) The plasma plume absorption is taken into account.

(4) The ceramic materials considered are semitransparent at 1.06 μm. Moreover, in the interaction process the material is being decomposed and a thin layer is formed on the surface when its temperature exceeds 1800 K for Si_3N_4.[11] Al_2O_3 is melted at temperatures higher than 2300 K and its absorptance increases dramatically.[12] For this reason a change of the type of the equivalent heat source from a volumetric to a surface one is considered during the laser pulse irradiation after reaching the temperatures mentioned.

(5) The material density does not vary with the temperature.

(6) The thermal properties of the ceramics change with the temperature.

(7) The reflectivity of the surface of the material also changes; once the above mentioned temperatures are reached, the reflectivities of the liquid silicon and aluminum are taken into account.

The laser drilling was modeled using the following one-dimensional heat-transfer equation:

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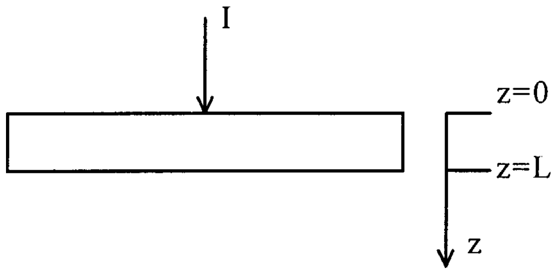

FIG. 1. Schematic the laser drilling arrangement.

$$C\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} K \frac{\partial T}{\partial z} + A(z,t), \tag{1}$$

where C is the heat capacity of the material, ρ is the density of the material, K is the heat conductivity, t is the temporal variable, and A is the heat source defined as

$$A(z,t) = I(t)(1-R)\alpha \exp(-\alpha z). \tag{2}$$

Here α is the absorption coefficient, R is the reflectivity of the material, and I is the laser power density, which was assumed to have Gaussian temporal shape with laser pulse duration τ_0 (half width at $1/e$ of maximum intensity level)

$$I(t) = I_0 \exp\left(-\frac{t^2}{\tau_0^2}\right). \tag{3}$$

The boundary conditions of the problem are:

$$T(z,0) = T_a, \tag{4a}$$

$$K \frac{\partial T}{\partial z} = P_1 \quad \text{at } z=0, \text{ and } T < T_e, \tag{4b}$$

where T_e is the evaporation temperature, and P_l represents the losses at the surface of the material given by

$$P_l = A_l \sigma (T^4 - T_a^4) + h_c (T - T_a), \tag{5}$$

where A_t is the gray-scale coefficient, σ is the Stephan–Boltzman constant, T_a is the ambient temperature, and h_c is the convection coefficient. The first term in Eq. (5) accounts for the reradiation losses and the second one for the convection losses. In our case we neglected the convection. The boundary problem for the back surface of the material slab is

$$-K \frac{\partial T}{\partial z} = P_{ll}, \tag{6}$$

where $-P_{ll}$ has the same form as Eq. (5). At $T = T_e$, the boundary value problem is

$$-K \frac{\partial T}{\partial z} = -\gamma \rho \frac{\partial g}{\partial t}, \tag{7}$$

where γ is the latent heat of evaporation and g is the erosion depth.

B. Numerical scheme

Equation (1) was solved together with the boundary conditions using the common forward time centered space finite difference scheme.[13] First, we solved Eq. (1) for linear coefficients, i.e., when K, C, and ρ do not depend on T. For this case, the finite difference scheme takes the form

$$T_q^{j+1} = T_q^j + \frac{\Delta t k}{h^2} (T_{q+1}^j - 2T_q^j + T_{q-1}^j) + \frac{k \Delta t A}{K}. \tag{8}$$

The sample is divided into n_z spatial slices (layers). Each slice is perpendicular to the z axis. The laser pulse is also divided into temporal slices, with a constant light intensity assumed within each temporal slice. In Eq. (8) q is the number of the slice, j refers to the jth moment and accounts for the temporal variation of the temperature, Δt is the temporal step, h is the spatial step, and $k = K/(C\rho)$ is the thermal diffusivity. The boundary value problem at $z=0$ has the following form:

$$T^{j+1} = T_1 + \frac{k\Delta t}{h^2} \left(T_2^j - T_1^j - \frac{P_l h}{K} \right) + \frac{k \Delta t A}{K}. \tag{9}$$

Here T_1 is the surface temperature. At $z=L$ the finite difference equation has the form

$$T_n^{j+1} = T_n^j + \frac{k\Delta t}{h^2} \left(T_{n-1}^j - T_n^j - \frac{P_{ll} h}{K} \right) + \frac{k A \Delta t}{K}, \tag{10}$$

with T_n being the temperature on the back surface of the slab.

For the case of temperature dependent thermal properties K, C, and hence k, the following scheme was used:

$$T_q^{j+1} = T_q^j + \frac{\Delta t}{h^2} (k_{q+1}^j T_{q+1}^j - 2k_q^j T_q^j + k_{q-1}^j T_{q-1}^j) + \frac{k_q^j \Delta t A}{K_q^j}. \tag{11}$$

The boundary problems were also modified in a similar way.

The stability criterion requires[13]

$$\frac{\Delta t}{h^2} \frac{K}{c \cdot \rho} \leqslant \frac{1}{2}, \tag{12}$$

where h is the computational step used along the z coordinate and Δt is the step used in the temporal domain. Evaporation of material takes place at $T \geqslant T_e$. The equation governing the removal of material is derived from the energy balance on the surface. The erosion depth g in the case of surface heat source is given by

$$\Delta g^j = \frac{(T_2^j - T_l^j) K^j \Delta t}{h \gamma \rho} + \frac{I^j (1 - R^j) \Delta t}{\gamma \rho}. \tag{13}$$

Equation (13) accounts for the fact that the energy of evaporation is the difference between the energy deposited into one element and the energy lost for compensation of the heat difference with the lower layer. R^j is the reflectivity of the material at the jth moment within the pulse.

The evaporation of the target leads to the formation of a plasma plume. In this case the attenuation of the light intensity is modeled by using the exponential form of Lambert's law with the plasma absorption coefficient α_{pl}.

TABLE I. Properties of Al_2O_3 and Si_3N_4 used in the calculations.

Parameter	Si_3N_4[a,b]	Al_2O_3[a,c]
Evaporation temperature T_e (K)	2150	3700
Decomposition temperature T_d (K)	1800	—
Melting temperature T_m (K)	—	2300
Heat capacity C (J kg^{-1} K^{-1})	7×10^4	1×10^4
Density ρ (kg m^{-3})	3.3×10^3	3.97×10^3
Thermal diffusivity k (m^2 s^{-1})	9.46×10^{-6}	1×10^{-4}
Heat of evaporation γ (J kg^{-1})	6.16×10^6	4.76×10^6
Reflectivity R	0.13	0.85
Absorption coefficient α (m^{-1})	2×10^4	3×10^4
Plasma absorption coefficient[d] (α_{p1} m^{-1})	1×10^6	1.5×10^6

[a]See Ref. 11.
[b]See Ref. 14.
[c]See Ref. 12.
[d]See Ref. 15.

III. EXPERIMENT

A Nd:YAG laser ($\lambda=1.06\,\mu$m, pulse width 10 ns at FWHM; repetition rate 1 Hz) operating in the TEM_{00} mode was used for drilling Si_3N_4 and Al_2O_3 ceramics targets. The laser pulses were focused on the samples by a specially built optical system consisting of a combination of an expander and an objective with a focal length of 50 mm forming a beam radius of 10 μm (at $1/e$ point from the maximum intensity) in the focal plane. The total depth drilled by five consecutive laser pulses was examined and measured using an optical microscope.

IV. RESULTS AND DISCUSSIONS

Equation (1) was solved and the results were compared with the experimental data. The properties of the ceramics used in the simulations are presented in Table I. These values are at 300 K. The temperature dependences of the thermal and optical properties were taken from Refs. 12, 14, and 16. All calculations begin with assuming a volumetric heat source. As we mentioned before, when a laser beam is focused onto a Si_3N_4 sample, decomposition into liquid silicon and gaseous nitrogen takes place.[11] The approximate temperature of the decomposition reaction is 1800 K. Above this point, a thin silicon layer is created on the surface. Since the silicon has a higher absorption coefficient ($\sim10^5\,\mathrm{cm}^{-1}$) compared to this of Si_3N_4, a change from a volumetric to a surface heat source was assumed at the corresponding moment of the laser pulse. The same change of the type of heat source is applied in the case of Al_2O_3. However, melting of the material is the reason why an increase in absorptance occurs.[12]

The effect of the change in the type of the equivalent heat source is evident from Fig. 2 for the case of Si_3N_4 [Fig. 2(a)] and Al_2O_3 [Fig. 2(b)]. Up to 1800 K (4.4 ns after the onset of the laser pulse), the rate of increase of the temperature is estimated at 285 K ns^{-1} in the case of Si_3N_4. However, it increases dramatically to 11×10^3 K ns^{-1} regardless of the fact that the reflectivity R of the material also increases. In the case of Al_2O_3 (4.8 ns after pulse onset), this change is pronounced even more strongly—from 368 K to 15×10^3 K ns^{-1}.

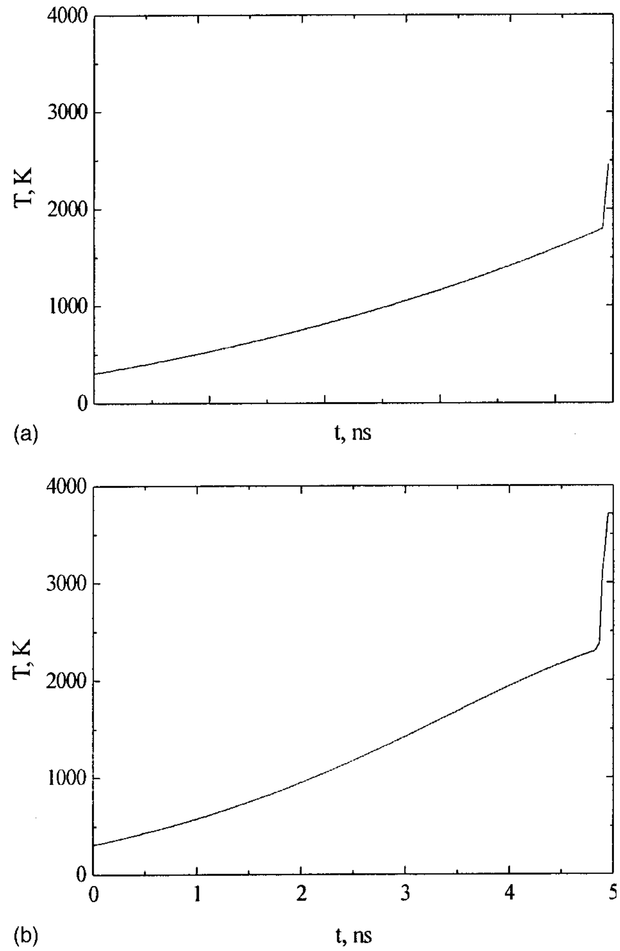

FIG. 2. Temporal dependence of the temperature on the surface of Si_3N_4 (a) and Al_2O_3 (b) during pulsed laser irradiation. The energy density is 200 J·cm^{-2}. The laser pulse duration (FWHM) is $\tau_0=10$ ns.

The dependence of the hole depth g on the energy fluence for Si_3N_4, calculated and experimentally obtained, is shown in Fig. 3. As it is seen, when the plasma absorption is not taken into account, the theoretically evaluated drilling

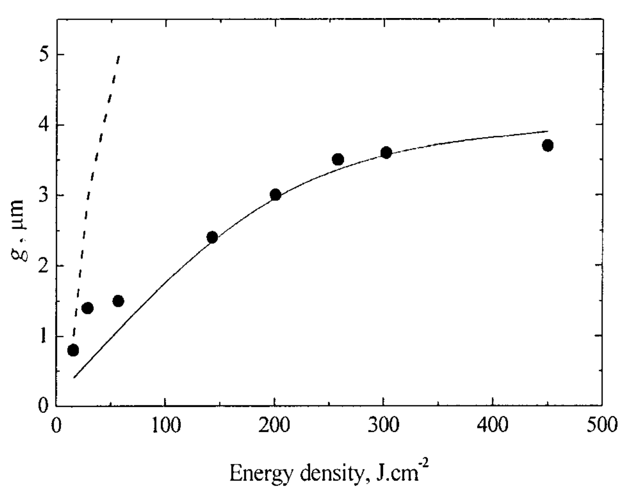

FIG. 3. Erosion depth g per pulse for a Si_3N_4 target as a function of the laser fluence. The simulation curves without (dashed line) and with (solid line) plasma absorption taken into account. The dots represent the experimental data.

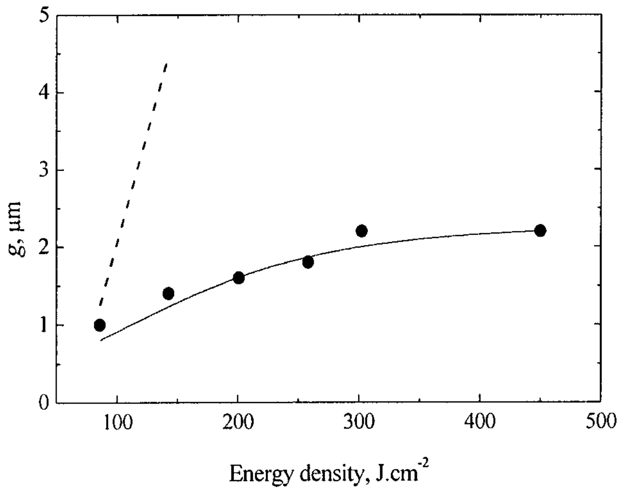

FIG. 4. Erosion depth g per pulse for an Al_2O_3 target as a function of the laser fluence. The simulation curves without (dashed line) and with (solid line) absorption of the plasma taken into account. Dots represent the experimental data.

depths g are close to the experimental values for the very low energy densities only (less than 30 $J\,cm^{-2}$). At higher fluences the discrepancy is dramatic. However, when the absorption of the plasma created on the surface of the material is taken into account, the theoretically estimated values of the erosion depth per pulse (Fig. 3—solid line) agree very well with the experimental ones.

Similar results were obtained in the case of Al_2O_3. Figure 4 shows the dependence of the hole depth on the energy fluence. Only when the absorption of the plasma is taken into consideration, does the calculated erosion depth per pulse agree well with the experimental data.

As one can see from Figs. 3 and 4 a discrepancy is observed between the experimental and theoretical erosion depths at lower laser fluences (up to 100 $J\,cm^{-2}$ for Si_3N_4 and up to 150 $J\,cm^{-2}$ for Al_2O_3). The reason is that a constant value of the plasma absorptance is considered in the calculation for the whole interval of fluences. However, α_{pl} depends on the laser intensity.[17]

V. CONCLUSIONS

We present the results of an experimental investigation of the process of laser drilling of Si_3N_4 and Al_2O_3 ceramic plates using a Q-switched Nd:YAG laser. A one-dimensional numerical model was developed and the heat transfer equation was solved in order to explain the experimental results observed. The change of the equivalent heat source from volumetric to surface during the laser pulse was also included in the model. Moreover, the absorption of the plasma plume formed on the surface of the ceramics was taken into account. The latter resulted in a good agreement between the theoretical and experimental results. Further investigations involving other materials are in progress and will be the subject of a forthcoming article.

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